NASA Contractor Report CR-195888

Final Report on the Analysis of Rapidly Developing Fog at the Kennedy Space Center

Prepared By:
Applied Meteorology Unit

Prepared for:
Kennedy Space Center
Under Contract NAS10-11844

NASA
National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1994

(NASA-CR-195888) THE ANALYSIS OF
RAPIDLY DEVELOPING FOG AT THE
KENNEDY SPACE CENTER Final Report
(Ensco) 68 p

N94-34939

Unclas

G3/47 0008492

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Executive Summary

The visibility rule in effect for all End of Mission (EOM) Space Transportation System (STS) landings at Kennedy Space Center (KSC) states: *"The weather element limits contained in this rule must be satisfied with observations at the GO/NO-GO decision time and with the forecast for landing time.... Restrictions to surface visibility include smoke, haze, fog, dust and clouds.. The 7 SM limit..."* This rule was designed to protect against a visibility problem developing unexpectedly within 90 minutes (i.e., after the de-orbit burn decision and before landing). In order to enhance the weather community's understanding of the precursors responsible for fog development at the Shuttle Landing Facility (TTS) and to develop tools to improve fog forecasting skill in support of the Space Shuttle Program, the Applied Meteorology Unit (AMU) developed a database of hourly surface observations from TTS and upper-air observations from Cape Canaveral Air Force Station (CCAFS) for a five-year (1986-1990) period.

Once this database was completed, a comprehensive analysis was performed. All fog events within the period were identified, and the onset and dissipation times were determined for each fog event. In addition, a detailed analysis was performed on 36 TTS fog events characterized by rapid deterioration of visibility. As part of that analysis the fog events were categorized as either advection, pre-frontal or radiation. As a result of these analyses, the AMU developed a fog climatological database, identified fog precursors and developed forecaster tools and decision trees.

The fog climatological analysis indicates that during the fog season there is higher risk for a visibility violation at KSC during the early morning hours (0700 to 1200 UTC), while 95% of all fog events have dissipated by 1600 UTC. A high number of fog events are characterized by a westerly component to the surface wind at KSC (92%) and 83% of the fog events had fog develop west of KSC first (up to 2 hours) as reported at Orlando and Daytona Beach.

A major goal of the study was to identify fog precursors that could be used up to 12 hours in advance. To address this the AMU developed fog decision trees and forecaster tools and utilities. Using the decision trees as process tools ensures the important meteorological data are not overlooked in the forecast process. Using the tools and utilities, key fog precursors can be monitored and evaluated out to 48 hours. Then by monitoring the low level precursors using the utilities developed by the AMU, the forecaster can monitor and observe the trends in the 54 foot local tower wind flow (westerly flow increase chance for fog formation), the low level inversion from 6 to 492 feet (the stronger the inversion the better the chance for fog formation), and the relative humidity values at tower 313 from 54 to 492 feet (relative humidity reading at or above 70% are needed for fog formation at KSC).

Key results from the analyses performed in this study are:

- Many precursors associated with fog development such as low level inversion, local tower wind flow at the 54 foot level (westerly flow), and low level moisture (up to 300 feet) can be monitored using existing sensor networks.

- Using decision trees and utilities for monitoring key elements of the local data sets, the forecaster can monitor environmental conditions and forecast the likelihood of visibility restrictions due to fog or stratus.

- A high number (92%) of the fog events analyzed show a westerly component to the surface wind. In many events, a westerly shift in the winds is apparent in the wind tower data prior to the fog development.

- For the advection and pre-frontal events, 83% of the events had fog develop in the Orlando to Daytona Beach area up to 2 hours prior to development at TTS.

- The primary onset time for fog development at TTS is between 0700 to 1200 UTC. Almost 95% of all fog events had dissipated (visibility improved to 5 miles or greater) by 1600 UTC and 75% of the cases improved by 1400 UTC.

- A low level inversion at or below 500 feet is generally present.

- Fog can develop even in the presence of strong winds at 492 feet above the surface. In these cases, the top of the inversion would be below 500 feet.

- The vast majority of the rapid visibility deterioration events occurring between 1986 and 1990 were either pre-frontal or advection fog events. Only two of the events were associated with radiational cooling.

With these tools and a better understanding of fog formation in the local KSC area, the Shuttle weather support forecasters should be able to give the Launch and Flight Directors a better KSC fog forecast with more confidence.

Briefly, the recommendations from the rapidly developing fog evaluation are:

- Transition the fog decision trees and fog forecasting utilities to operational use.

- Upgrade the MESONET wind towers by installing up to 4 visibility sensors on towers west of the Banana River.

1.0 Introduction

The work described in this report was performed under the National Aeronautics and Space Administration (NASA) Applied Meteorology Unit (AMU) Task 003. The purpose of this task is to develop data bases, analyses, and techniques leading to the improvement of the 90-minute forecasts made for Space Shuttle Program (SSP) landing facilities in the continental United States and at the Trans-Atlantic (TAL) sites. The sub task addressed in this report concerns fog development that would affect the less than 7-statute mile visibility rule for End-Of-Mission (EOM) Shuttle landings at Kennedy Space Center (KSC) (Rule 4-64(A)). The rule states the following:

> *"The weather element limits contained in this rule must be satisfied with observations at the GO/NO-GO decision time and with the forecast for landing time.... Restrictions to surface visibility include smoke, haze, fog, dust and clouds. The 7 SM limit is the horizontal distance component from the runway threshold that correlates to the 10k feet altitude point on the outer glide slope."* (Johnson Space Center, 1991).

The AMU's work under this sub task is to:

1. Develop a data base for study of fog associated weather conditions relating to violations of this landing constraint;
2. Develop forecast techniques or rules-of-thumb to determine whether or not current conditions are likely to result in an acceptable condition at landing;
3. Validate the forecast techniques; and
4. Transition techniques to operational use.

The results of the Shuttle Flight Rule Workshop on Fog, held on 20 January 1988 (NASA Johnson Space Flight Center, 1988) were reviewed for this report. One of the main questions asked at the workshop was "Can a statement 95% or better confidence be made if a seven plus mile visibility forecast is made for landing prior to de-orbit?". The workshop participants unanimously agreed, "that a reliable 1 1/2 hour forecast of no fog violation of visibility constraints in rule 4-64(A) at the landing site area could be made with current forecasting technology and measurements / observational systems being employed for support of the Space Transportation System operations regardless of seasonal or daily variations."

However, the requirement to issue a 95% confidence no fog forecast causes a high false alarm rate in positive fog forecasts. It is anticipated the enhanced understanding of fog development in the Cape Canaveral vicinity along with the forecasting aids resulting from this investigation will reduce the false alarm rate for positive fog forecasts at the Shuttle Landing Facility.

This report is organized as follows: Section 2.0 describes the data base used to organize the surface and rawinsonde data and the procedures employed to prepare the data for analysis. Section 3.0 describes the analysis procedures applied to each of the selected 36 events. Section 4.0 discusses the results of the overall fog climatology analysis. Section 5.0 describes the development of the fog forecasting utility tools. Section 6.0 presents the preliminary fog forecast rules and skill scores for the fog precursors. Section 7.0 contains the summary and the recommendations from this study. Finally, Appendix A presents two case studies for two of the three types of fog events.

2.0 Data Preparation and Case Selection

For this investigation, the fog season for Cape Canaveral was defined as beginning October 1 and ending April 30. Though fog occurs during other parts of the year, this period has the highest number of fog occurrences at TTS (Shuttle Landing Facility or SLF). During this period the sunrise varies by 67 minutes from 1209 UTC to 1102 UTC. Since the sunrise variation is not too large, the compositing of key elements from each fog event is based on UTC time instead of sunrise time.

This study made extensive use of the surface data base developed for the AMU Two Tenths Cloud Cover Study (Atchison, 1993). This data base includes hourly surface observations (no special observations) from TTS and upper-air observations from the Cape Canaveral Air Force Station (CCAFS) rawinsonde site (74794) for the five year period, 1986 to 1990. dBase IV was selected to store and process the data.

The TTS surface data were obtained from the Marshall Space Flight Center (MSFC). Upper-air observations were obtained from the Computer Sciences Raytheon (CSR) Meteorology Section and from the USAF Environmental Technical Applications Center (ETAC). Other data obtained to augment the cloud cover data base included local wind tower observations from KSC/CCAFS; surface data for Daytona Beach (DAB), Orlando (MCO and ORL), Patrick AFB (COF), Melbourne (MLB), Vero Beach (VRB) and Avon Park (AGR); and upper air data for the southeastern United States. The local wind tower data were obtained from KSC/CCAFS and the surface and upper air observations were obtained from the National Climatic Data Center.

In addition to the data on electronic media, hard copies of surface observations on Forms 10a and 10b, and the Daily Weather Map weekly series were also used in this analysis. These forms were obtained from the 45th Weather Squadron, National Climatic Data Center, and ENSCO, Inc.

Key weather elements available for analysis from the surface observations include:

- Ceiling Height
- Present Weather
- Sea-level Pressure
- Visibility
- Wind Speed
- Wind Direction
- Temperature
- Total Cloud Cover
- Cloud Amounts
- Dew Point Temperature
- Cloud Heights

This study focused on rapidly developing fog and/or stratus that developed between decision time and landing that would result in a violation of the SSP Flight Rule 4-64(A). This was defined as fog and/or stratus that developed within one hour at TTS, reducing the visibility to 7 statute miles or less and/or a ceiling developed below 2500 feet within the hour. A two step process was used to identify the rapidly developing fog events which met the above criteria.

First, all events which satisfied the following criteria were identified:

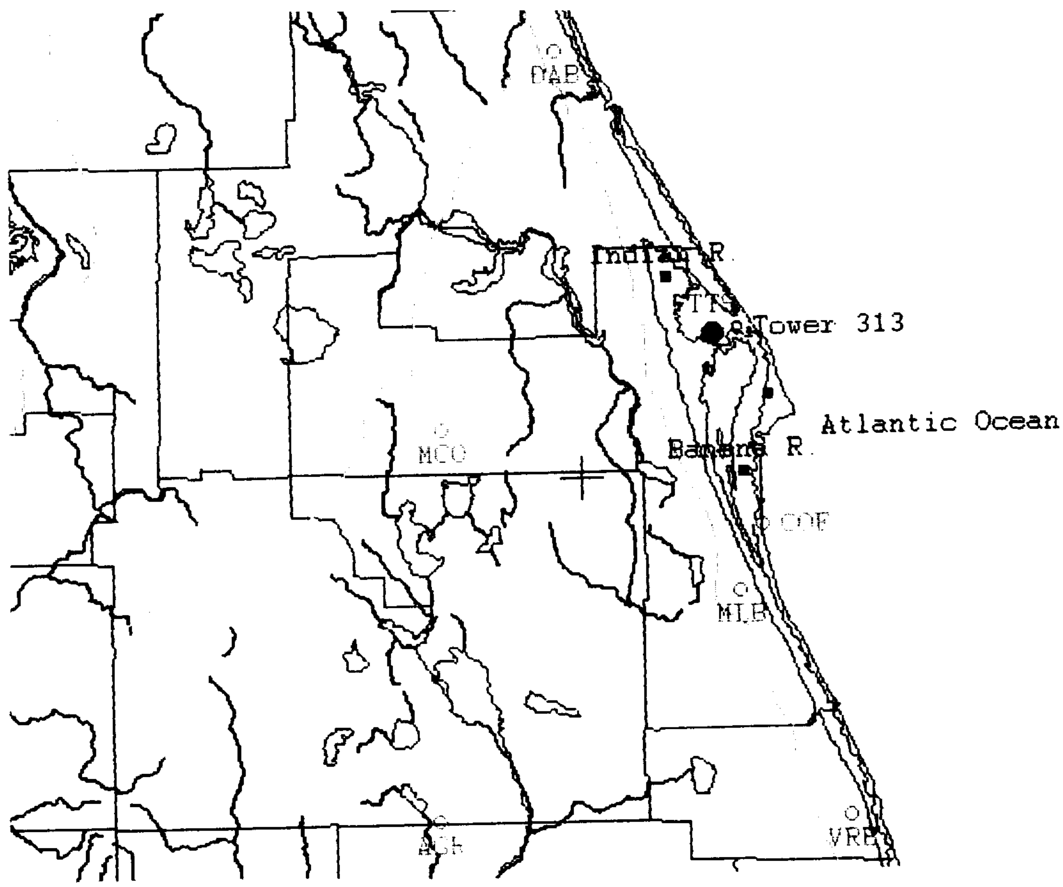
- Fog and/or stratus having a ceiling less than 2500 feet and/or visibility less than 7 statute miles due to fog at TTS, between the hours of 0500 and 1600 UTC.

This query identified 172 cases within the five year data period. The 172 events were manually reviewed by using the TTS Form 10's and reduced to 36 cases that are representative of the challenging EOM fog forecast at KSC (i.e., onset of fog is coincident with the rapid deterioration of visibility). These 36 fog event cases were analyzed in detail from the surface up to 500 mb and the knowledge gleaned from these cases was used to develop the fog precursor criteria, analyze the Air Force developed Fog Stability Index (FSI) and develop the fog forecast decision trees.

Space Shuttle Program Flight Rule (4-64) also states that 5 statue miles can be used as the Go/No-Go decision visibility constraint when the Precision Approach Path Indicators (PAPI's) are visible and forecast to remain visible and if a weather reconnaissance aircraft is available (which is generally the case). Consequently, the complete 5 year data base was also analyzed to determine the onset and dissipation times for all fog events using both 5 and 7 miles as the selection criteria. The results of these queries are presented in Section 4, Fog Climatology, and will allow the forecaster to compare differences in the fog onset and dissipation times for the two visibility criteria.

3.0 Data Analysis Procedures

The goal of the analysis was to determine local synoptic and mesoscale conditions favoring development of fog at TTS. This was accomplished by analyzing the conditions over the southeastern United States with emphasis on central Florida from the surface to 500 mb. Analyses were performed for the event day as well as plus and minus one day. Case files consisted of the upper air analyses for 500, 700, and 850 mb for each 12-hour period, surface analysis maps from the Daily Weather Map series and the surface weather observations from Daytona Beach, Orlando, Titusville, Patrick AFB, Melbourne, Vero Beach, and Avon Park. Figure 3.1 illustrates the location of these stations throughout central Florida.



DAB= Daytona Beach, MCO= Orlando, TTS= Shuttle Landing Facility, COF= Patrick AFB
MLB= Melbourne, VRB= Vero Beach, AGR= Avon Park
Figure 3.1. Map of Central Florida

The first step in the analysis was to develop a complete synoptic summary of each case. This included analyses of both surface and upper air data. The upper air analyses focused on identification of all relevant pressure, thermal, wind, and moisture features from 500, 700, and 850 mb over the southeastern United States. The surface analyses highlighted the placement and movement of fronts and temperature and moisture patterns across Florida. In addition, time series of cloud cover, surface visibility, temperature, dew point, and wind were generated for each central Florida surface observation site. These time series identified the onset time when each station's visibility decreased to less than 7 miles with fog.

The next step was to develop a surface analysis trend package for each case. By using the surface Form 10a's from each of the 9 surface stations, a detailed surface analysis of central Florida was created and analyzed at least for every three hours and, where necessary, for each hour. These surface analyses were developed for the day preceding each analyzed fog event through the event. A total of over 600 surface weather charts were plotted and analyzed. A detailed surface analysis summary for each fog case was also generated. The summaries consisted of a synoptic and mesoscale analysis along with a description of the precursors or key information for each case.

In addition to the synoptic surface data, local rawinsonde and tower data (See Figure 3.2 for location of towers) were analyzed for each case. The local rawinsonde analysis focused on the strength of the low level inversion and the moisture distribution. The local wind tower data analysis focused on the low level wind flow and its change with time.

In addition to the detailed analysis of the 36 case studies, the complete 5 year data base was queried to identify every fog event day using two different selection criteria. The first query identified all days characterized by visibility less than 7 miles due to fog. The fog onset and dissipation times as well as predominant wind flow were determined for the 352 fog events identified by the first selection criteria. The second query identified all fog days at TTS with visibility less than 5 miles. As with the data from the first query, the fog onset and dissipation times as well as predominant wind flow were determined for the 280 fog events identified by the second selection criteria. The results of these two analyses are presented in Section 4, Fog Climatology.

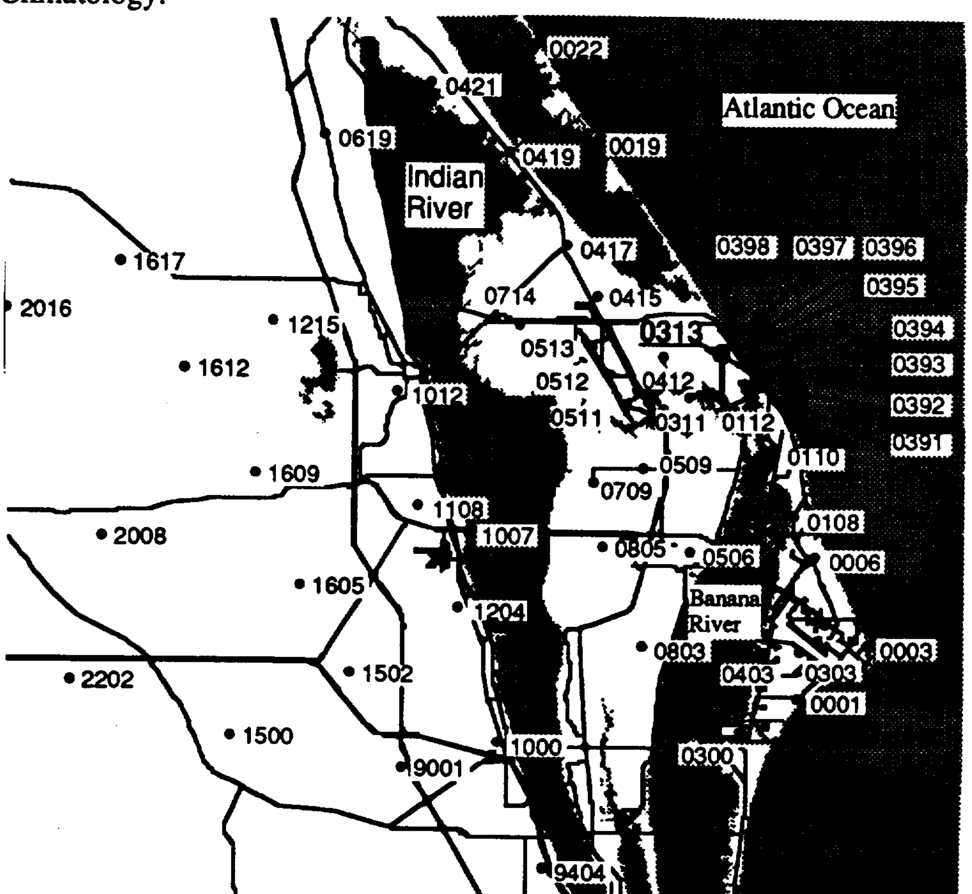


Figure 3.2. Location of the Kennedy Space Center/Cape Canaveral AFS Wind Towers

4.0 Fog Climatology

The topography of the Cape Canaveral vicinity is an important factor in the development of fog at TTS. The numerous large water bodies play an important role in the development of local thermally-driven circulations and also serve as sources of low-level moisture, both important to fog development. Consequently, knowledge of the Cape Canaveral topography is required to fully understand the fog climatology of the local area.

KSC and CCAFS are almost totally surrounded by large bodies of water with the Atlantic Ocean on the east, the Banana River in-between and the Indian River to the west (See Figure 3.2). The land consists of sandy soil covered with heavy growths of low palmetto and brushwood vegetation in undeveloped areas. The land rises from sea level to 10 to 20 feet in undulating sand dunes falling away to mangrove swamp at the Banana River. The surroundings are primarily typical flat Florida table land. It is composed of large areas of lakes (Poinsett to the north, Winder in the middle and Washington to the southwest) and rivers (St. Johns about 12 miles to the west), marshes, orchards, and timber land. Between the CCAFS and the St. Johns River lie the Banana and Indian rivers which are not rivers in the traditional sense but are saltwater lagoons with no discernible flow other than tidal variations. Depths range from less than a foot in the marshy shallows to approximately 30 feet in the main channels.

The relatively flat terrain and the numerous land and water interfaces have significant effects upon local weather conditions. The numerous water bodies provide additional sources of low level moisture. If the surface pressure gradient is weak, the early morning surface temperature differences between the land and the Atlantic Ocean drive a land breeze circulation. During the winter and early spring months, the direction of the land breeze ranges from southwest to northwest with speeds of 5 to 7 knots.

4.1 General Fog Characteristics

Although only 36 events over a 5-year period were analyzed (Table 4.1), some important trends in fog formation were noted. The fog events fell into three categories: advection, pre-frontal, and radiation. Category definitions are listed in Table 4.2.

The typical advection fog event is characterized by fog developing west of TTS, sometimes over to Orlando or north toward the Daytona Beach area, generally to the north of a surface ridge line. The low level relative humidity as indicated by tower 313 is greater than 70% from surface up to 295 feet. The surface wind directions reported by the tower network are generally westerly, 180-360° and, in time, gradually veer to a more northwesterly direction prior to the fog moving into TTS. This report includes 21 of these cases.

Pre-frontal fog events are very similar to the advection fog events. A pre-frontal event is characterized by a slight veering in the surface winds from southwest to west-northwest as the front moves closer to TTS. In many of the events, a weak surface ridge moves south of the Cape Canaveral area several hours before the fog moves into TTS. This report includes 13 of these cases.

Some general statements can be made about radiation fog based on climatology (Cape Canaveral Forecast Facility, Terminal Forecast Reference Notebook) (45th Weather Squadron, 1988), and this study. Radiation fog generally forms near sunrise (the time of occurrence of the two radiational fog events in the study are 1141 UTC and 1248 UTC). Surface winds are typically light (3 to 5 knots) and variable. If fog develops when the speed is at or above 3 knots, the direction is generally from 180° to 360°. The Cape Canaveral or Tampa rawinsonde data typically indicate low level moisture (at or below 900 mb) and dry air aloft. This report includes 2 of these cases.

Some general characteristics of fog formation (i.e., moisture distribution, low level mixing, etc.) are also given. All local fog precursors and key points are stated in Section 8.0 Summary and Recommendations.

Table 4.1. Individual Fog Case Data

Date	Type of fog	Fog West Prior to TTS Onset	Hrs Prior to TTS Onset	Fog Stratus	TTS Fog Onset Time (UTC)	Fog Break-up Time(UTC)	Veering Wind at Towers	Prevailing Wind Direction	Prevailing Wind Speed (kts)	Inversion Strength (°C)
7-Feb-86	P	yes	2	F/S	1009	1825	yes	210	7	4
25-May-86	A	no	0	F	0834	1208	yes	280	2	6
7-Sep-86	P	yes	3	F/S	0719	1450	no	230	4	1
15-Nov-86	P	yes	1	F/S	0707	2255	yes	310	5	3
18-Nov-86	A	yes	2	F/S	0913	1314	yes	300	2	*3
20-Dec-86	A	yes	1	F/S	1109	1555	yes	220	3	3.5
24-Apr-87	P	yes	3	F/S	1025	1345	no data	240	5	*3
27-Oct-87	P	yes	1	F/S	0648	1338	yes	270	4	1
28-Nov-87	A	yes	1	F/S	0634	1430	no	340	3	*1.5
27-Dec-87	A	yes	2	F	0809	1407	yes	320	2	8
17-Feb-88	A	yes	2	F	1028	1245	no	340	4	11
1-Mar-88	A	yes	2	F/S	0742	1542	yes	280	9	*4
6-Apr-88	P	no	0	F	0500	1140	yes	180	3	11
24-Apr-88	A	yes	2	F/S	0932	1318	no	200	4	2
15-Jul-88	A	yes	2	F/S	0907	1318	no	240	5	*1.5
4-Oct-88	P	yes	2	F/S	0807	1200	yes	260	4	1.5
9-Dec-88	A	yes	1	F	0918	1430	no	310	1	9
11-Jan-89	P	yes	2	F/S	0500	1408	no	350	6	0
8-Feb-89	P	yes	2	F/S	1203	1539	yes	260	1	1
13-Mar-89	A	yes	2	F/S	1011	1410	yes	250	6	6
14-Mar-89	A	yes	1	F/S	0740	1710	no	250	6	*6
9-Apr-89	P	yes	1	F/S	0943	1423	no	210	4	5
27-Apr-89	A	yes	1	F	0905	1236	yes	0	0	*4
17-May-89	P	no	0	F/S	0546	1249	yes	250	1	5
2-Sep-89	A	yes	3	F	0950	1115	yes	240	1	4
15-Oct-89	A	no	0	F/S	0523	1420	yes	320	2	2
30-Oct-89	P	yes	2	F/S	0850	1540	no	340	6	0
22-Nov-89	A	yes	1	F/S	0813	1710	yes	290	7	*4
27-Dec-89	R	yes	1	F/S	1141	1530	yes	280	3	6
1-Jan-90	P	yes	3	F/S	0906	1215	yes	210	8	*12
7-Jan-90	A	yes	2	F/S	0718	1640	yes	40	2	3
21-Jan-90	A	yes	1	F/S	0916	1550	yes	270	3	4
10-Feb-90	R	no	0	F/S	1248	1401	no	200	8	0
29-Apr-90	A	yes	3	F/S	0910	1423	yes	220	5	3
16-Dec-90	A	yes	1	F	0524	1330	yes	250	1	7
23-Dec-90	A	no	0	F	0930	1337	yes	220	2	5

P = Prefrontal Fog
R = Radiation Fog
A = Advection Fog

F = Fog
S = Stratus
* Subsidence Inversion

Table 4.2. Fog Classification

Classification	Criteria	Description
Advection (21 events)	• Weak high pressure over Florida. Surface ridge axis needs to be south of TTS. • Fog develops west of TTS (St. Johns River valley - Orlando - Daytona Beach) first. • Sounding is moist below 900 mb and dry above 850 mb. • Prevailing surface wind direction is 180° - 360° and local tower data shows a NW shift. • Tower 313, 6 to 492 ft inversion of 3° to 5 °F.	• Allows inversion to form and surface wind flow becomes a westerly drainage flow. • Fog forms west of TTS (St. John River valley - Orlando - Daytona Beach) first, generally to the north of a surface ridge line (1 - 2 hours). • Local tower data shows a westerly wind component (180° - 360°) and in time the data will show a veering of the wind component prior to the fog moving into TTS.
Pre-Frontal (13 events)	• Presence of a moving frontal boundary, Florida panhandle to TTS. • The front will pass through TTS during the fog event day. • TTS sounding is moist below 900 mb and may have moisture above. • Weak surface pressure gradient ahead of front.	• Fog occurs ahead of front as wind flow veers to a more westerly flow. • First indications are reports of fog west of TTS (Orlando and/or Daytona Beach). • The KSC/CCAFS wind tower data will report a westerly wind component (180° - 360°) at 54 feet.
Radiation (2 events)	• Sounding has low level moisture (900 mb and below) • Will be dry aloft (above 850 mb). Fog occurs at or near sunrise. • Surface winds will be light. Land breeze may develop, (240° - 340°) on local towers just prior to fog development. • Some central Florida stations may report 4 to 6 miles visibility due to fog.	• Fog forms near sunrise with initial heating and mixing of the lower atmosphere. • Surface winds are light and variable, from 180° - 360° for speeds above 3 knots.

Advection and pre-frontal fog events have similar basic characteristics. Both types of fog events are generally associated with:

- The advection of fog into the TTS area from the west.
- Moist environments (dew point depression of 3°C (5°F) or less) at and below 900 mb on the Cape Canaveral rawinsonde.
- TTS surface and local tower wind directions are generally from 180° to 360°.
- Local wind tower 313 usually indicates RH values above 70% from 6 to 295 feet.

The main differences between advection and pre-frontal fog events are:

- Moisture above 850
  - •• Prefrontal may be moist (temperature - dew point spread of 3°C (5°F) or less) above the low levels due to the advection of clouds ahead of the front.
  - •• Advection generally associated with dry conditions (temperature - dew point spread of 5°C or more) above 850 mb.
- Fog development area
  - •• The fog development area for advection fog is generally just west of TTS (the St. Johns River basin). However, the fog development area is related to the location of the surface ridge axis and can be further west or north of TTS (e.g. towards Orlando or Daytona Beach).
  - •• The fog development area for prefrontal fog depends upon the location of the front at fog formation time. The fog development area is generally to the northwest of TTS, but can be near Orlando or Daytona Beach.

Key similarities and differences between the fog types are illustrated in Table 4.3.

Table 4.3. Fog Type Characteristics (Precursors)

Fog Characteristic	Advection	Pre-Frontal	Radiation
Moist (Dew point depression <= 3° C (5°F)) below 900 mb on sounding	√	√	√
Moist (Relative Humidity > 70%) from surface to 295 feet on tower 313	√		√
Dry (Dew point depression > 5° C (9°F)) above 850 mb	√		√
Frontal system in area		√	
Surface dew point depression of 0-5°F (0-3°C)	√	√	√
Local wind towers indicate direction between 180-360° (tower data)	√	√	
Fog advects over TTS from the west	√	√	

4.2 Analysis of Fog Events (1986 - 1990)

The following sections (4.2.1 through 4.2.6) present the results of the detailed analyses of the 36 fog cases. Also included in these sections are the results of the fog onset and dissipation time analysis for all fog cases during the 5 year period. Throughout this section the following symbols will represent the defined data sets:

- 5-mile_{36} - Visibility less than 5 miles for the 36 case study events.
- 7-mile_{36} - Visibility less than 7 miles for the 36 case fog events.
- 5-mile_{all} - Visibility less than 5 miles for all fog cases.
- 7-mile_{all} - Visibility less than 7 miles for all fog cases.

4.2.1 Analysis of the Fog Onset Times at TTS

Figures 4.1 and 4.2 present the initial time when the TTS visibility dropped below 7 and 5 statute miles, respectively, for the 36 fog events. Part of the similarity in the distribution of fog onset times can be attributed to criteria used to select the 36 fog events (rapidly developing fog, see Section 2). The visibility at TTS for a majority of these events was less than 5 miles on the first report of fog development. Therefore, the fog onset time for the two different criteria was the same. In 30 of the 36 cases fog developed between 0800 and 1300 UTC. In addition, the data indicate fog onset times for prefrontal fog were fairly evenly distributed throughout the time period. However, the frequency of fog onset for advection fog peaks at 0900 to 0959 UTC.

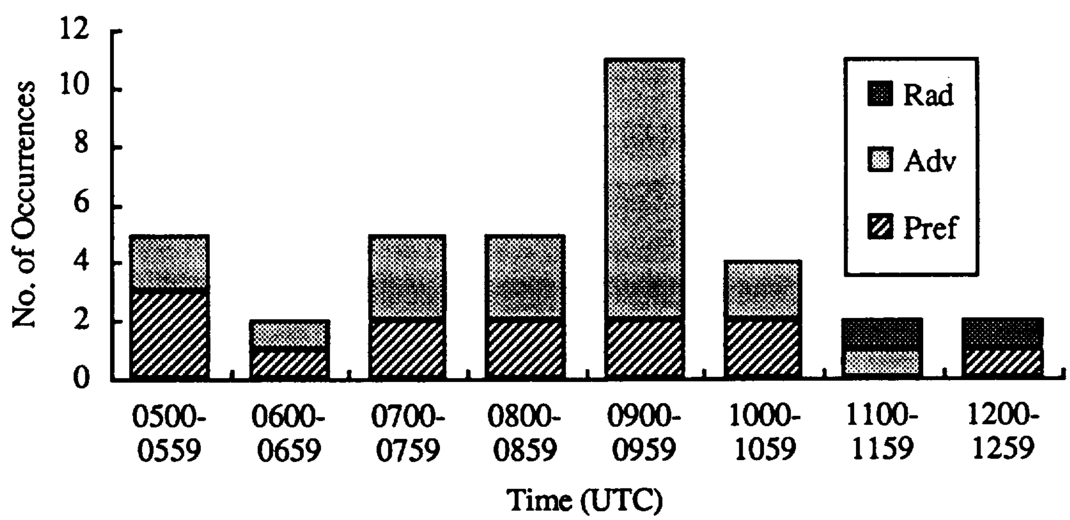


Figure 4.1. Time of Fog Onset at TTS for the 36 Fog Events (Visibility less than 7 miles).

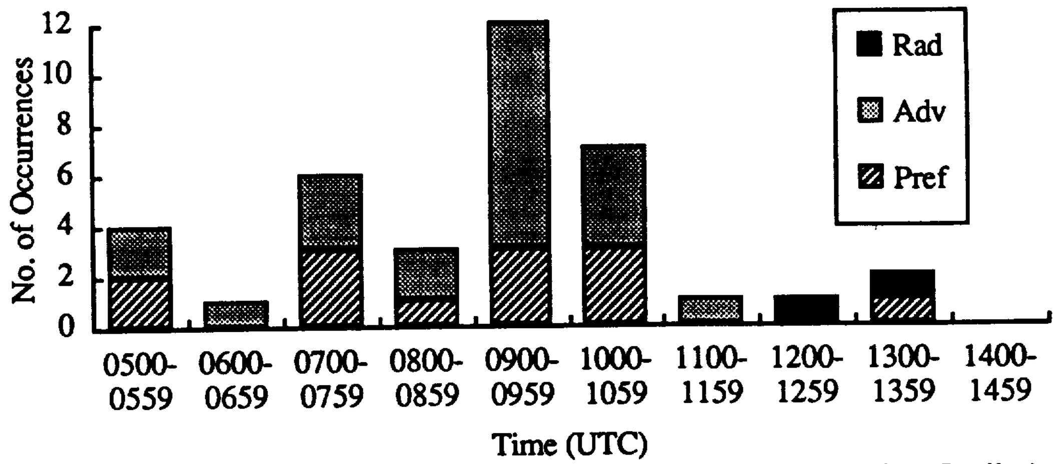


Figure 4.2. Time of Fog Onset at TTS for the 36 Fog Events (Visibility less than 5 miles).

The fog onset times for all fog cases are shown in Figures 4.3 and 4.4. The fog onset times for the 7-mile$_{all}$ data set (Figure 4.3) have a similar distribution to the onset times from the 7-mile$_{36}$ events (Figure 4.1). In particular, the time period with the highest frequency of occurrence of fog onset (i.e., 0900 to 0959 UTC) is the same for both data sets (i.e., all fog events and the 36 case study events). However, the distribution of fog onset times for the 5-mile$_{all}$ fog cases (Figure 4.4) is different from both the distribution of fog onset times to the 7-mile$_{all}$ fog cases (Figure 4.3) and the distribution of fog onset times to the 5-mile$_{36}$ case study events (Figure 4.2). Specifically, the time period with the highest frequency of occurrence of fog onset for the 5-mile$_{all}$ fog cases is one hour later (e.g., 1000 to 1059 UTC) than the corresponding time periods for the 7-mile$_{all}$ fog cases and to the 5-mile$_{36}$ case study events. In addition, the frequency of fog onset times for the 5-mile$_{all}$ fog cases is more uniformly distributed among a number of time periods (e.g., 0900 to 1259) whereas the frequency of fog onset times to the 7-mile$_{all}$ fog cases and to the 5-mile$_{36}$ case study events peaks at 0900 to 0959 UTC.

The explanation for the differences in the fog onset time distributions is based on the differences between the composition of the data sets. The 36 case study events are all characterized by rapid deterioration of visibility due to fog. Consequently, the distributions of fog onset times for the 7-mile$_{36}$ case study events and to the 5-mile$_{36}$ case study events are similar. However, the all fog events samples contain fog events which are characterized by rapid deterioration of visibility due to fog as well as fog events characterized by *gradual* deterioration in visibility. The fog onset times for the 5-mile$_{all}$ fog cases will be later than the fog onset times to the 7-mile$_{all}$ fog cases for the events characterized by *gradual* deterioration in visibility. Consequently, the distribution of the fog onset times for the 5-mile$_{all}$ fog cases will be different than the distribution of the fog onset times of the 7-mile$_{all}$ fog cases and different than the distribution of the fog onset times to the 5-mile$_{36}$ case study events.

Another factor which may account for some component of the differences in the fog onset time distributions is not all of the fog events included in the distribution of onset times for the 7-mile$_{all}$ fog cases are included in the distribution of onset times to the 5-mile$_{all}$. This is because the visibility did not drop below 5 miles in some of the fog events included within the visibility less than 7 mile sample.

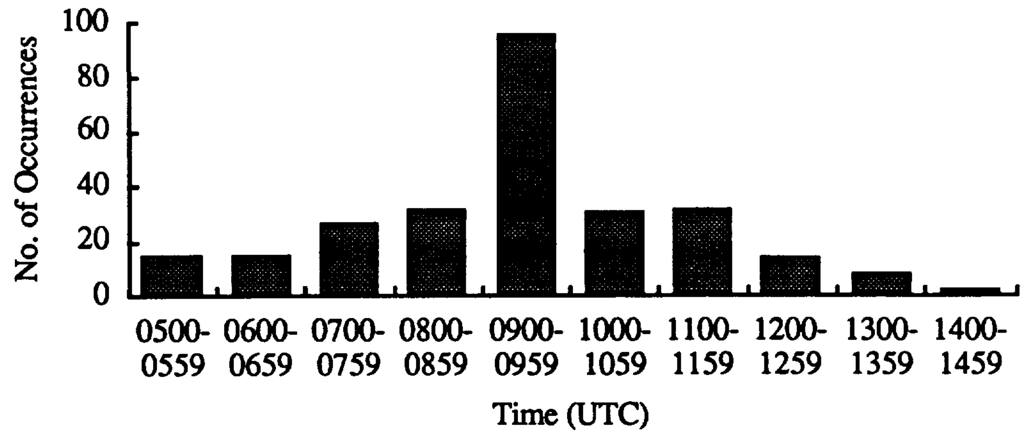


Figure 4.3. Fog Onset for the period 1986 - 1990 (Visibility less than 7 miles, 335 events).

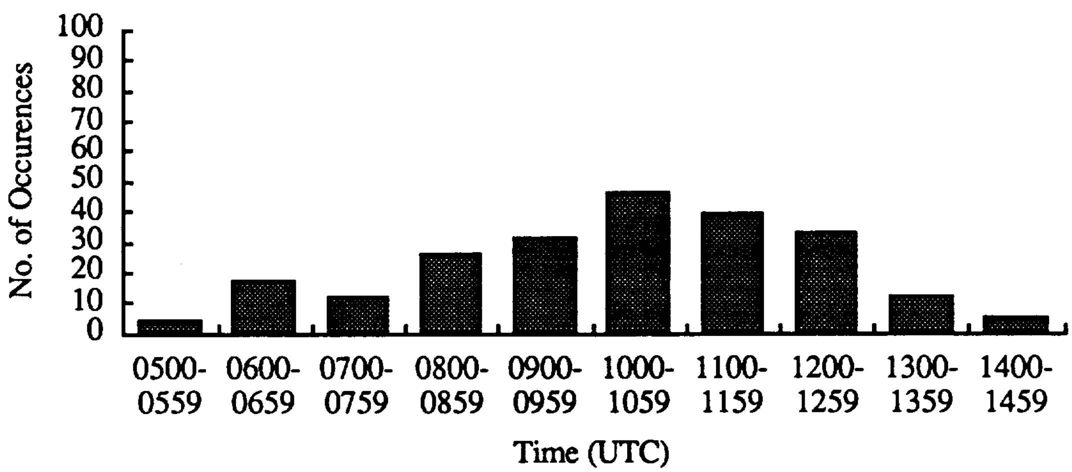


Figure 4.4. Fog Onset at TTS for the period 1986 - 1990 (Visibility less than 5 miles, 267 events).

4.2.2 Analysis of the Fog Dissipation Times

Figures 4.5 and 4.6 present the frequency of occurrence of the time when the visibility at TTS improved to at least 7 or 5 miles, respectively, for all 36 fog events. These figures indicate that in about 95% of the fog events the fog had dissipated by 1600 UTC. The general tendency for the fog to dissipate at TTS by no later than 1600 UTC can be very useful in forecasting and planning of the Space Shuttle de-orbit operations. Combining the information from this section and Section 4.2.1, it is evident that the primary hours of fog occurrence at TTS affecting visibility are from 0800 to 1600 UTC.

Figures 4.7 and 4.8 present the times when the visibility at TTS improved to at least 7 or 5 miles, respectively, for all fog cases between 1986 and 1990. As with the case study sample, the time of fog dissipation at TTS for the complete 5 year data base is typically between 1200 and 1600 UTC. In particular, the fog dissipated for most of the fog events (i.e. 96%) by 1600 UTC. Most of the fog events characterized by dissipation after 1600 UTC are associated with frontal boundaries.

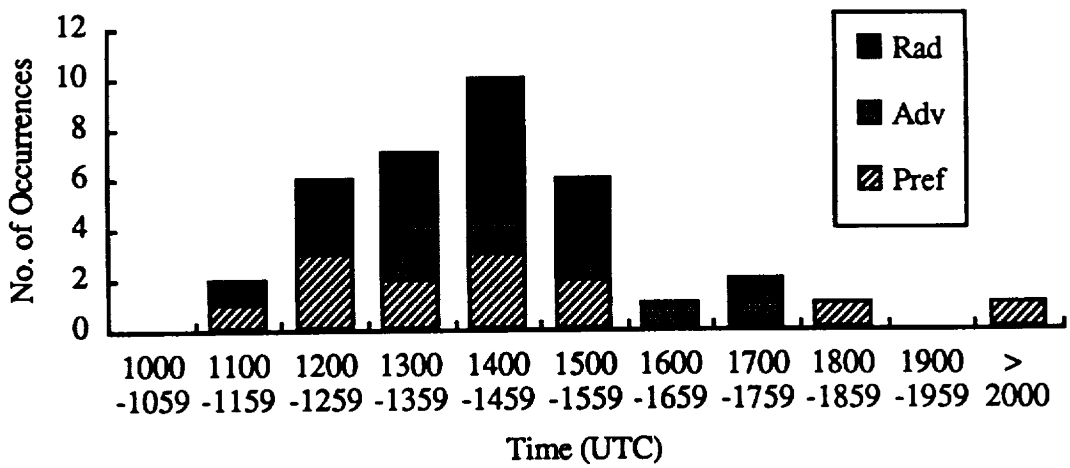


Figure 4.5. Time of Fog Dissipation at TTS for the 36 Fog Events (Visibility less than 7 miles).

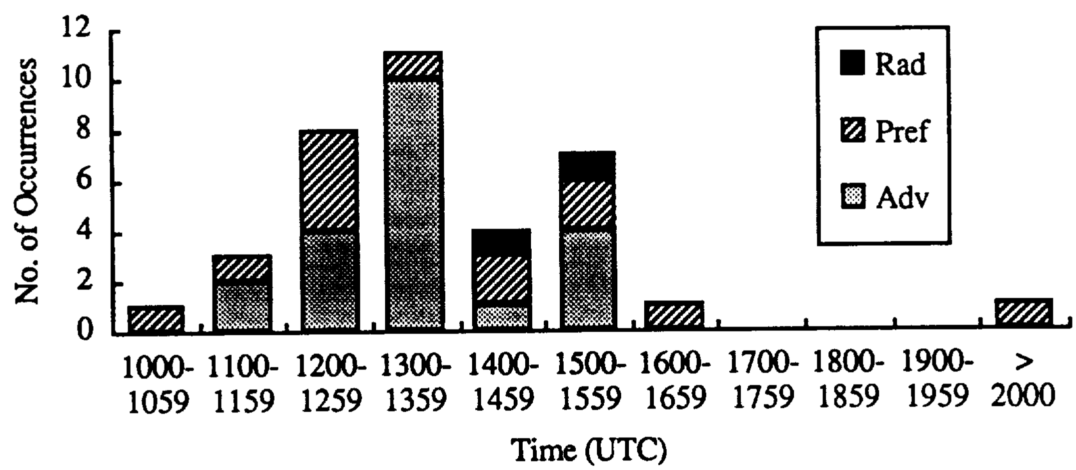


Figure 4.6. Time of Fog Dissipation at TTS for the 36 Fog Events (Visibility less than 5 miles).

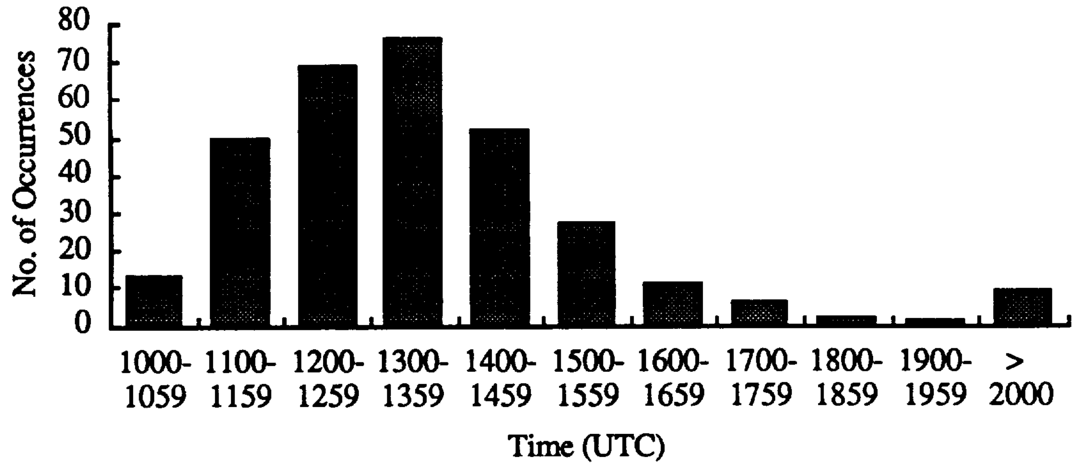


Figure 4.7. Time of Fog Dissipation at TTS for the period, 1986 - 1990, (Visibility less than 7 miles), 335 Fog Events.

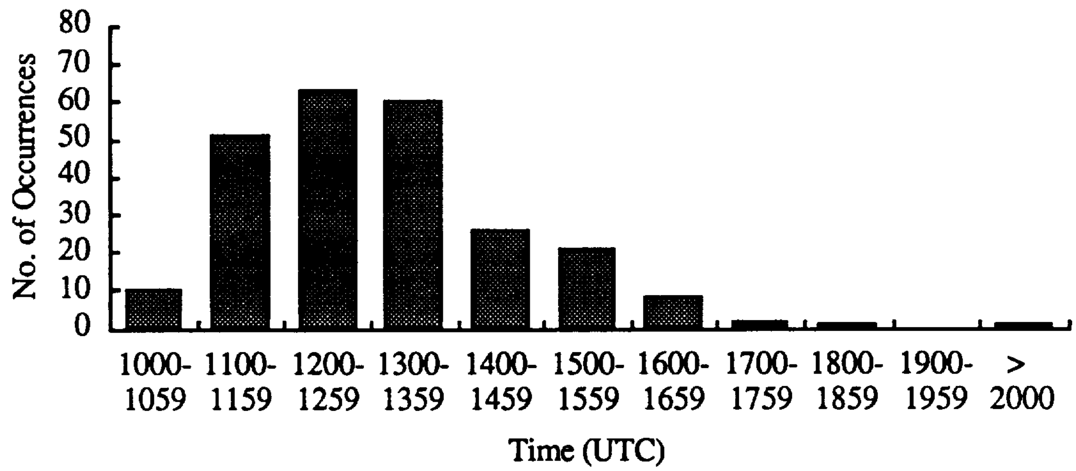


Figure 4.8. Time of Fog Dissipation at TTS for the period, 1986 - 1990, (Visibility less than 5 miles) 267 Fog Events.

4.2.3 Analysis of the Wind Direction at Time of Fog Development

Figure 4.9 illustrates the TTS's reported wind direction at fog onset (i.e., when the visibility at TTS decreased to less than 7 miles). The data indicate the prevailing wind direction at TTS for most fog events included a westerly wind component (180° - 360°). Of the 36 events, 34 reported a westerly surface wind component and nearly half of the events had a surface wind direction from 240° to 299°. Only two events reported a wind direction outside of the 180° - 360° sector. Calm winds were reported at TTS at the time of fog onset in one of the events (27 April 1989). However, northwest winds of 3 to 5 knots were reported up to two hours before the fog formation. In the second event, the wind direction at TTS was northeast (7 January 1990). This event has been categorized as an advection type event because the surface winds from several towers around TTS were northwest.

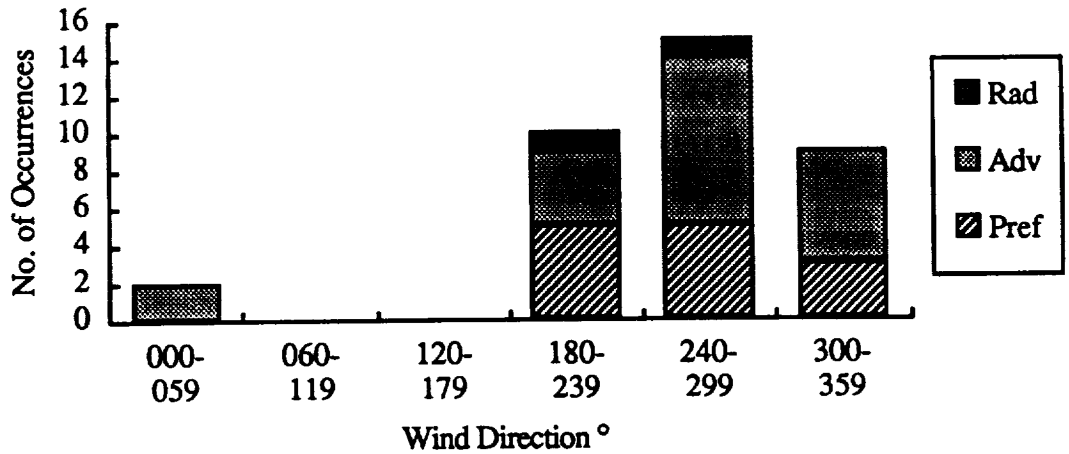


Figure 4.9. Surface Wind Direction at Time of Fog Onset at TTS (Visibility less than 7 miles, 36 Fog Events).

As shown in Figure 4.10, almost all the fog events were characterized by light winds. Of the 36 fog events, only 1 event (an advection event on 1 March 1988) had a wind speed above 8 knots. All the other fog events had wind speeds less than or equal to 8 knots when the fog developed at TTS. Furthermore, the data indicate the observed wind speed at TTS at the time of fog onset was generally 5 knots or less. Very low wind speeds at TTS (i.e. calm to 2 knots) were reported in 12 of the 36 events.

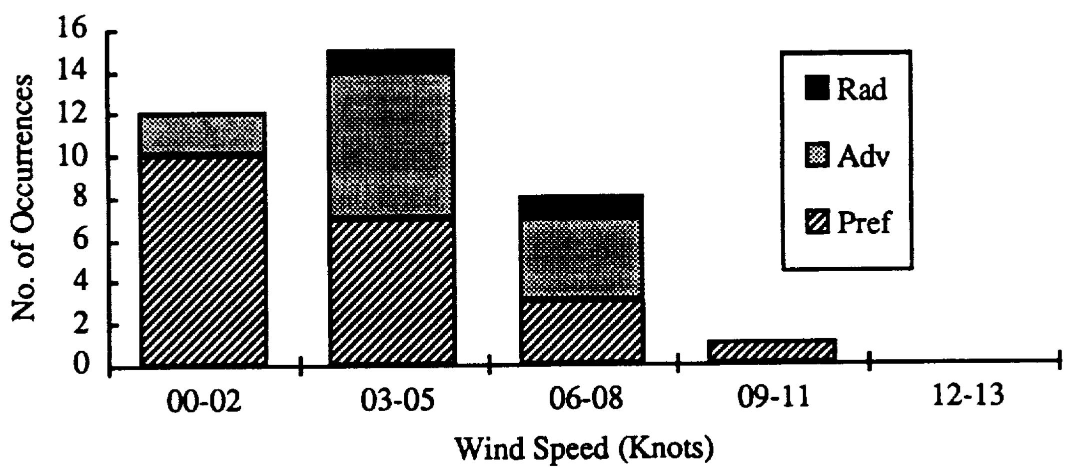


Figure 4.10. Surface Wind Speed at Time of Fog Onset at TTS .

Figure 4.11 shows the wind speeds measured at tower 313 at the 492 foot level at fog onset time at TTS. Wind speeds at the 492 foot level are much higher than surface winds. In 13 out of the 36 fog events, wind speeds at 492 feet were greater than or equal to 15 knots. This indicates that fog can occur at TTS even when there is a strong gradient flow aloft.

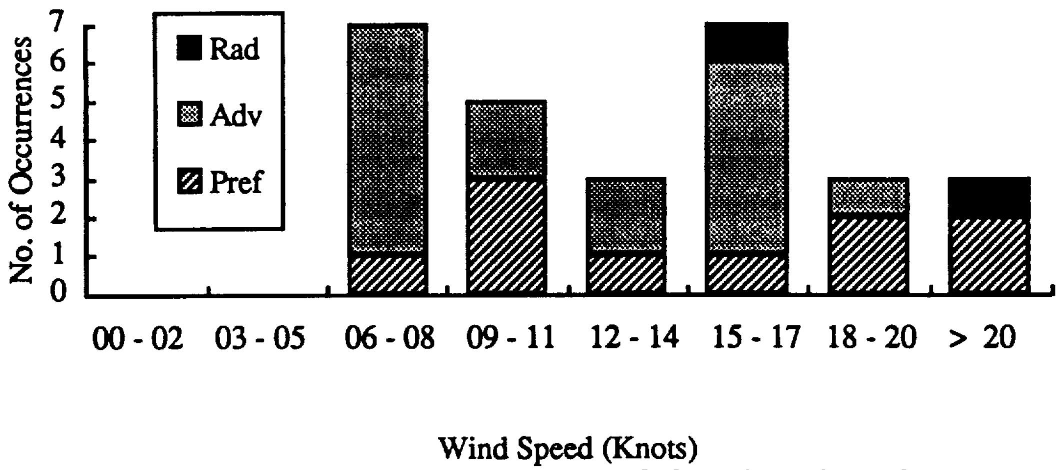


Figure 4.11. Wind Speed at the 492 foot Level at Tower 313 at Time of Fog Onset.

Lack of cloud cover is also a factor in fog formation. In the majority of the fog events, no ceilings were in the TTS surface observation in the evening or early morning prior to fog development. The lack of clouds facilitates the radiational cooling needed for fog development. Of the events with a mid to high level ceiling reported on the TTS observations prior to fog development, one was categorized as radiation, three as advection, and three as pre-frontal. For most of these events, the ceilings were not in the area for the entire nighttime period and thus did not significantly hinder radiational cooling. It is important to note that some of the ceiling reports may be in error due to the lack of light for viewing the celestial dome during the nighttime.

4.2.4 Analysis of the Advection Fog Events from the 36 Fog Cases

This section discusses the advection fog events. Of the 36 fog events, over half (21 events) were categorized as advection fog. As stated in Table 3.2, fog events were classified as advection if they met the following criteria:

- Fog developed in the Orlando and/or Daytona Beach area first.
- Local tower data indicated a veering westerly wind between 0500 and 1300 UTC prior to fog formation.

Figure 4.12 indicates that 17 of the 21 events reported fog development at TTS between the hours of 0700 to 1100 UTC and that in 11 of the 21 events fog developed between 0900 and 1100 UTC.

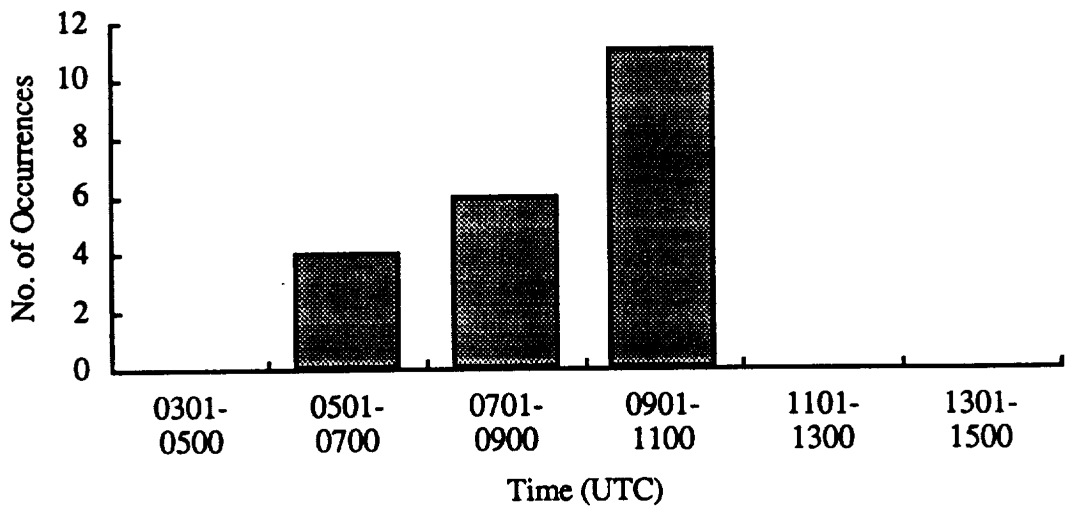


Figure 4.12. Time of Fog Onset at TTS for the Advection Events.

Figure 4.13 shows the time of fog dissipation (visibility increased to 7 miles or greater). Two groups of hours predominate. The fog dissipated in 8 events between 1200 to 1359 UTC. Those events are associated with the dissipation of light fog and stratus where the top of the fog layer was below the top of a weak inversion. This allows the atmosphere to quickly warm and mix, thereby dissipating the fog and stratus shortly after sunrise. The 9 events characterized by fog dissipation between 1400 and 1559 UTC were associated with stratus where the visibility decreased to less than 1 mile and/or the ceiling was below 200 feet. These events were characterized by a stronger low level inversion. For these 9 events the fog thickened right after sunrise with the initial surface heating and low level mixing but dissipated by 1600 UTC.

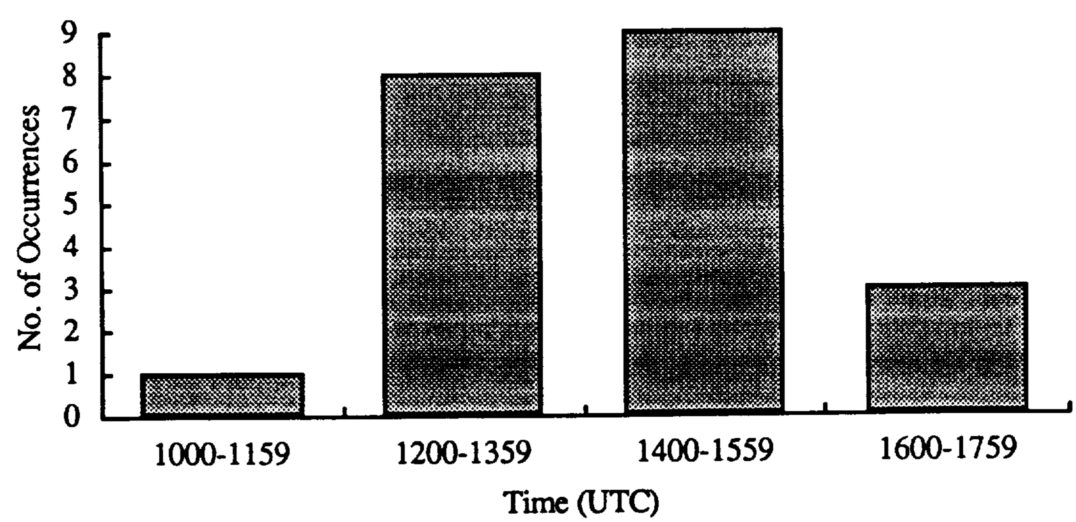


Figure 4.13. Time of Fog Dissipation at TTS for the Advection Events.

Figure 4.14 indicates the majority of the advection events were associated with a west to northwest wind at the time of fog onset at TTS. Of the two events which did not have a westerly wind component, one case was associated with calm winds at fog onset time at TTS; however, one hour prior, the surface winds were out of the northwest. In the other case, the fog formed at TTS at 0718 UTC with a northeast wind (040°). However, tower data to the west and north reported a northwest wind at fog onset time.

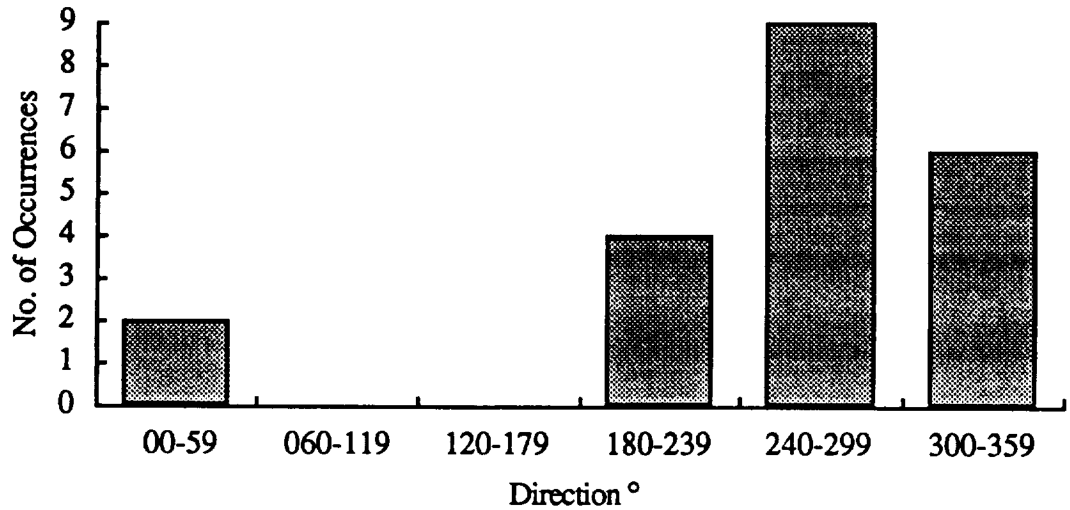


Figure 4.14. Surface Wind Direction at Time of Fog Onset at TTS for the Advection Events.

Figure 4.15 presents the surface wind speeds for the advection events at the time of fog onset at TTS. For all of the events, wind speeds were less than or equal to 9 knots. Of the 21 events, 17 reported surface wind speeds of 5 knots or less and a high number of the advection fog events had surface winds of 2 knots or less (10 of 21). It is important to note these light wind speeds were measured at the time of fog onset at TTS and may not be representative of the overall wind direction and speed prior to the fog development. When the speeds were averaged over several hours prior to fog formation the wind speeds would be in the range of 3 - 5 knots. This may indicate that at the exact time of fog development, the winds weakened slightly (a weakening of the land breeze) facilitating fog formation.

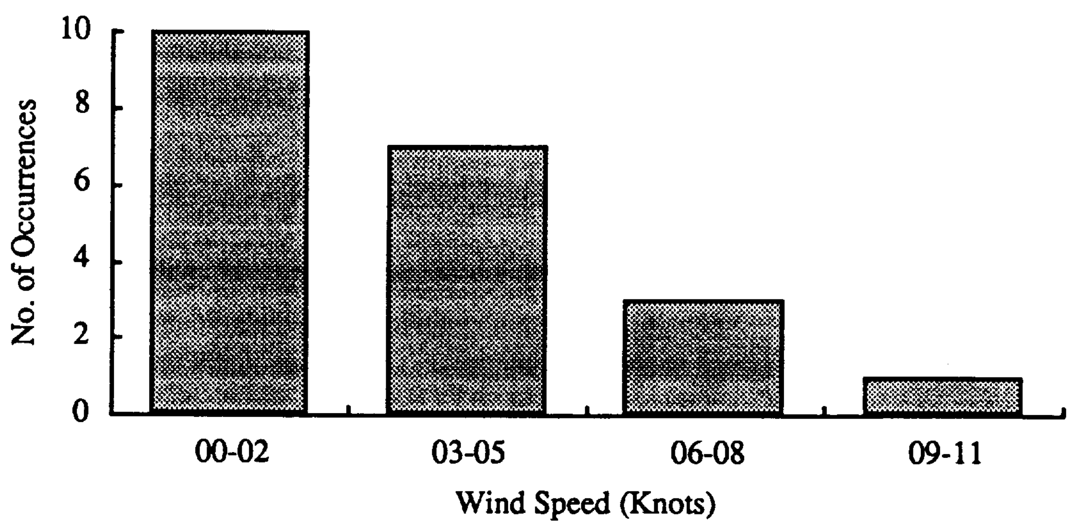


Figure 4.15. Surface Wind Speed at Time of Fog Onset at TTS for the Advection Events.

No ceilings were reported between the hours of 0500 and 1200 UTC in 18 of the 21 advection events. This is expected since clear skies or mostly clear skies are needed for significant radiational cooling and subsequent fog formation. Of the three events where a mid to high-level ceiling existed, only one case had a generally solid broken to overcast high-level cloud deck. The 18 November 1986 case had 8/10 of high cirrus clouds most of the night. Although 8/10 cloud cover is significant, some radiational cooling can occur with a high cirrus cloud deck.

4.2.5 Analysis of Pre-Frontal Fog Events from the 36 Fog Cases

As stated in Table 4.2, a pre-frontal fog event is characterized by:

- Presence of a moving frontal boundary, at least within the Florida panhandle, moving southeast, with frontal passage at TTS during the fog event day after fog formation.

Thirteen of the 36 fog events were classified as pre-frontal events. Even though the pre-frontal fog events are similar to the advection events, there are distinct differences between the two classifications. A frontal boundary can facilitate fog formation by either veering the surface winds as the boundary gets closer to the Cape or by weakening the pressure gradient over the Cape and allowing the land breeze to develop.

The pre-frontal events generally do not have a dry atmosphere above 850 mb. Some of the pre-frontal events are associated with mid to high-level broken cloud decks; and fog dissipation typically occurs later than in the advection events due to pre-frontal clouds inhibiting burn-off or post-frontal temperature inversion.

Figure 4.16 shows the time of fog formation at TTS for the pre-frontal events. There is a distinct difference between fog onset times for the pre-frontal and advection events (Figure 4.12). The time of fog formation for pre-frontal events is spread across an 11 hour period whereas the initial development of advection fog occurred between 0501 to 1100 UTC, only a 6 hour period. Also, the onset times for advection events peaked just before sunrise (0901 to 1000 UTC), whereas the pre-frontal events had a more uniform distribution of onset times between 0301 to 1300 UTC.

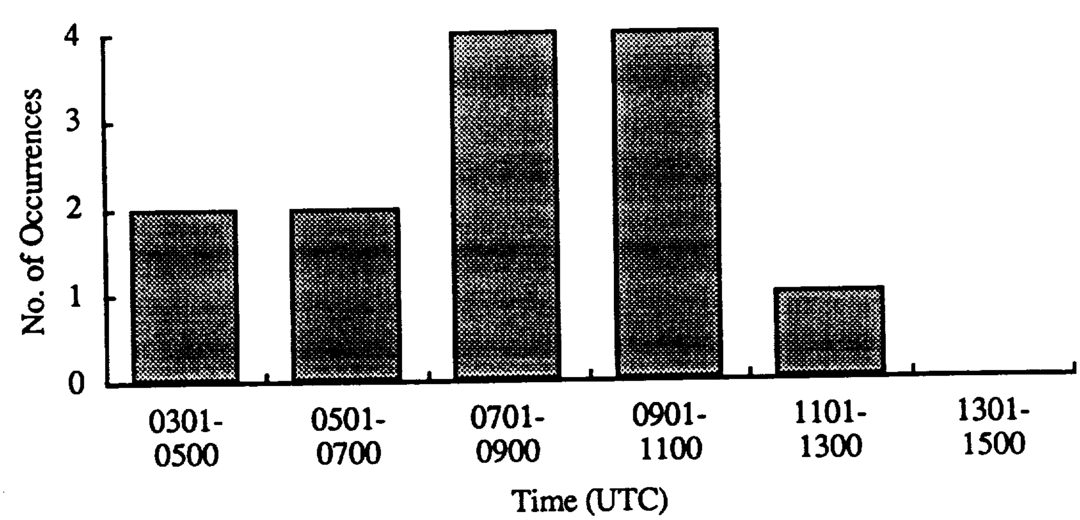


Figure 4.16. Time of Fog Onset at TTS for the Pre-Frontal Events.

Figure 4.17 displays the distribution of fog dissipation times for the pre-frontal fog events. Most events (11 of 13) had fog dissipation times earlier than 1600 UTC which is similar to the advection events. The two events where reduced visibility extended past 1600 UTC were associated with fronts that moved through the area during the late morning hours resulting in persistent stratus.

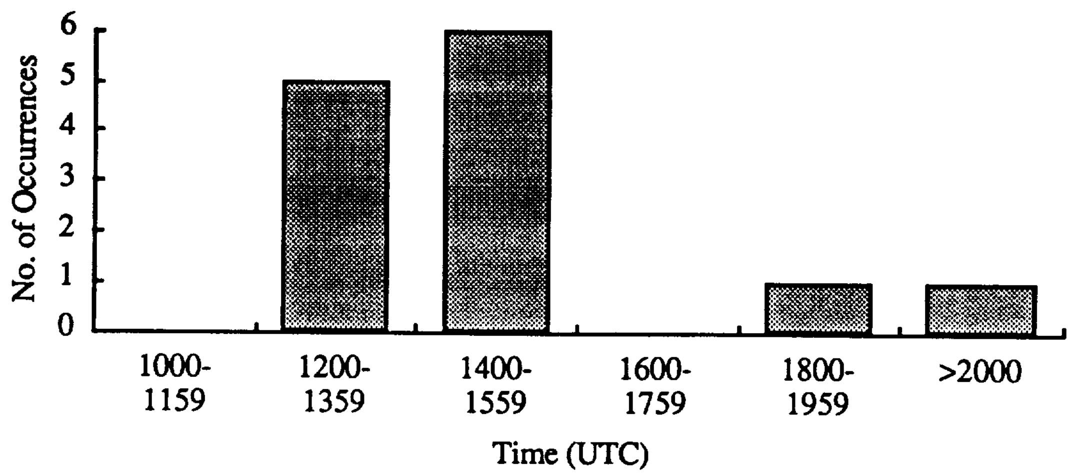


Figure 4.17. Time of Fog Dissipation at TTS for the Pre-Frontal Events.

As with the advection events, the prevailing surface wind directions (Figure 4.18) for the pre-frontal fog events indicate a westerly component (180° - 360°). This is expected since the prevailing wind flow ahead of the front normally contains a westerly component from the southwest to west or northwest as the cold front approaches TTS. Also, as a cold front approaches central Florida it generally slows and weakens. This can result in a weakening of the pressure gradient, allowing a land breeze (westerly wind flow) to develop. This scenario can often be observed in the local wind tower data.

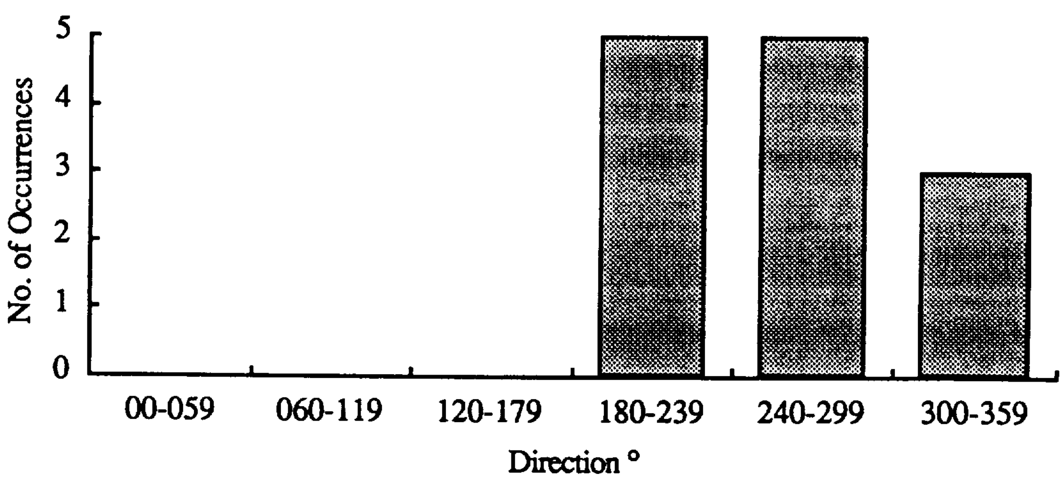


Figure 4.18. Surface Wind Direction at Time of Fog Onset at TTS for the Pre-Frontal Events.

The pre-frontal events were generally characterized by slightly stronger surface winds (3 to 8 knots) than the advection events (1 to 5 knots). A frontal system moving into the central Florida area and the induced southwest wind flow ahead of the front enhances the land breeze flow, thereby increasing the wind speeds slightly. Most pre-frontal events had wind speeds greater than 3 knots (12 of 14, see Figure 4.19) compared to the advection events in which only 11 out of 21 were characterized by wind speeds greater than 3 knots.

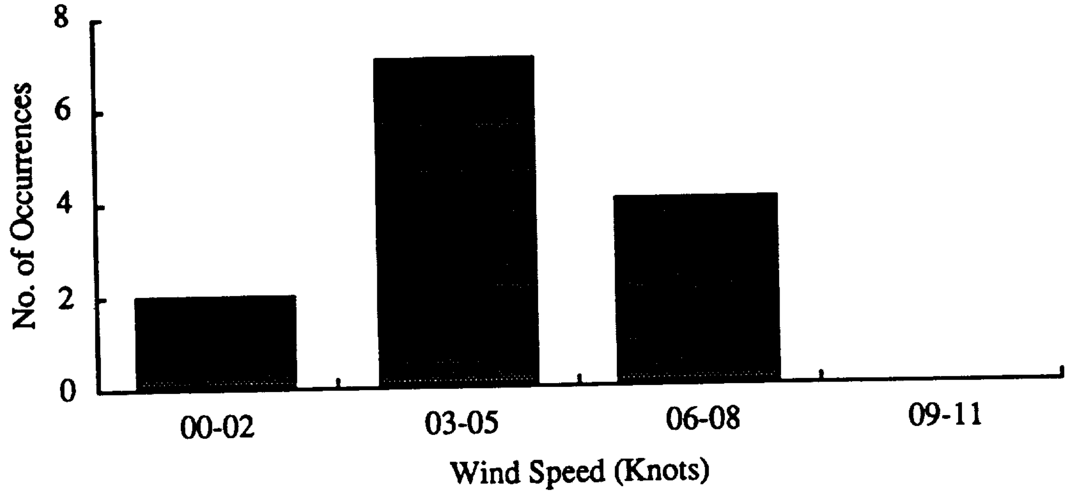


Figure 4.19. Surface Wind Speed at Time of Fog Onset at TTS for the Pre-Frontal Events.

Of the 3 classifications of fog analyzed in this report, only the pre-frontal events had a significant number of occurrences of mid to high-level ceilings -- 4 out of 13 events had ceilings from 0000 to 1200 UTC. These ceilings were associated with clouds developing ahead of the frontal system approaching the TTS area.

4.2.6 Analysis of Radiation Fog Events from the 36 Fog Cases

As stated in Table 3.2, a radiation event is characterized by:

- Light fog (4-6 miles visibility) in the central Florida area prior to development of fog at the Shuttle Landing Facility and development of fog at or near sunrise.

Only two of the 36 events were characterized as radiation fog events. For the event on 27 December 1989, TTS's visibility decreased to 1/2 mile with fog and a northwest wind at 3 knots just after sunrise (1202 UTC). By 1410 UTC, the fog thickened resulting in a 200 foot broken condition and 1/8 mile visibility. Daytona Beach was the only other station in central Florida with visibility less than 4 miles. Daytona Beach's visibility decreased to 1/8 mile with fog at 1333 UTC. Patrick AFB, just south of the Cape, had 5 miles visibility due to fog between 1255 and 1555 UTC.

The other radiation fog event occurred on 10 February 1990. On this day, TTS and the surface stations west and north of the Cape area reported fog near sunrise (sunrise was at 1240 UTC). Daytona Beach reported fog at 1133 UTC. TTS reported a scattered stratus layer at 1145 UTC and a ceiling at 1248 UTC. Orlando reported fog development at 1230 UTC.

Based on information from the Range Weather Operations (RWO) Terminal Forecast Reference Notebook (TFRN), local meteorological experience, and the two radiational fog events, some statements can be made about the radiation fog events.

First, the winds for both events were westerly indicating either the surface ridge line was south of the Cape Canaveral area or the surface pressure gradient was weak assisting the land breeze development. Both events were characterized by a gradual shift in the local tower wind flow to a more westerly flow during the early morning hours (0500 to 1000 UTC). Soundings from the previous evening (2200 to 2300 UTC) on both days indicated a drying of the atmosphere above 900 mb which facilitated subsequent radiational cooling. Both events were characterized by patchy ground fog and westerly surface winds the previous day. The fog and stratus dissipated by 1600 UTC for the two radiation fog events.

4.3 Fog Forecast Indices

This section of the report presents a description and analysis of a Fog Stability Index (FSI) developed by the Air Weather Service. The FSI as described in Air Weather Service Forecaster Memo 90/001 (Air Weather Service, 1990), uses several parameters to assess the likelihood of radiation fog development. The FSI formula is:

$$FSI = 4 * T_s - 2 * (T_{850} + T_{ds}) + W_{850}$$

- T_s = surface temperature in °C
- T_{850} = temperature at 850 mb in °C
- T_{ds} = surface dew point in °C
- W_{850} = 850 mb wind speed in knots

The memorandum lists the following guidelines for radiation fog forecasting:

Calculated FSI Value	Risk of Fog Formation
> 55	Low
31 - 55	Moderate
< 31	High

The limitation with the FSI formula is it can only be updated with a new rawinsonde sounding. Generally, there are three soundings per day during the week and only one or two per day during the weekends at Cape Canaveral. This means a FSI estimate could be computed around 1100, 1600 and 2300 UTC on a typical day. KSC/CCAFS has additional higher temporal resolution information on the stability and moisture distribution of the lower atmosphere (e.g. Tower 313 has sensors from 54 to 492 feet). The results from this investigation indicate that the atmospheric conditions in the lower 500 feet of the atmosphere are closely related to fog formation potential. Consequently, a new Fog Susceptibility Index (FSI313) using data from tower 313 was developed by the AMU. This index developed by the AMU can be computed or updated at least hourly giving the forecaster additional insight into the fog potential and the change in fog potential.

The new FSI (FSI313) formula is based on replacing the 850 mb data with the temperature and wind speed from the 492 foot sensor at tower 313. This allows the forecaster to update the FSI313 with every new TTS observation or every hour. The forecaster could also compute a new FSI313 every 5 minutes based on new tower data and the hourly TTS observation. The FSI313 formula is:

$$FSI313 = 4 * T_s - 2 * (T_{313} + T_{ds}) + W_{313}$$

- T_s = TTS surface temperature in °C
- T_{313} = temperature from tower 313 at 492 feet in °C
- T_{ds} = TTS surface dew point in °C
- W_{313} = wind speed in knots from tower 313 at 492 feet

The following paragraphs present the results of the analyses of the FSI and the FSI313 for the 36 case study fog events. Since the rawinsonde data from the evening prior to the fog event were not always available, the FSI was computed using the 1200 UTC rawinsonde data from the morning of the fog event along with the surface observation from TTS at the time of fog onset. The FSI313 was computed using data from tower 313 and the TTS surface observation at the time of fog onset.

The FSI estimates (Figure 4.20) for all events were in the moderate to high risk range. Furthermore, 26 of the 36 events were in the high risk category.

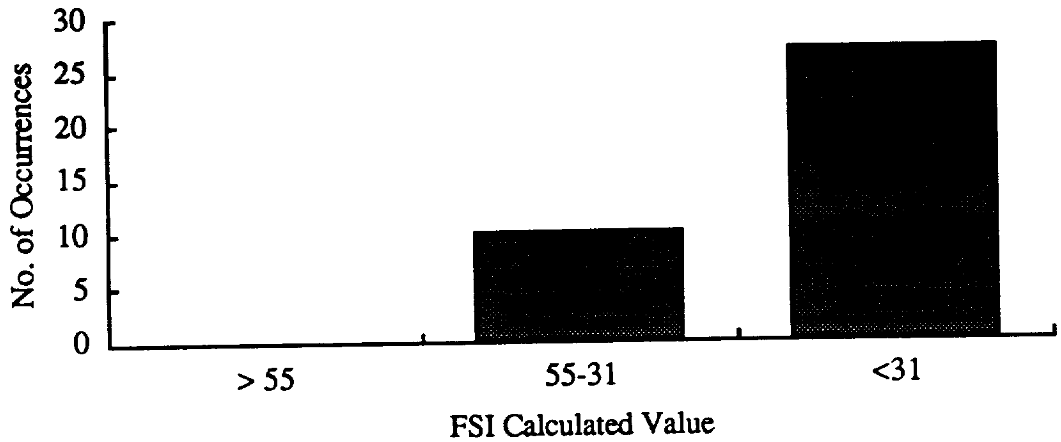


Figure 4.20. Fog Stability Index (FSI) for All Events.

The relationship between the FSI and the FSI313 for 27 of the 36 fog events is presented in Figure 4.21. Nine of the fog events were not included in this analysis because not all the data necessary to compute the FSI and the corresponding FSI313 were available. Although certainly not a perfect linear relationship, the graph does indicate some correlation between the two indices. Consequently, regression analysis was employed to test the significance of the correlation between the two fog indices.

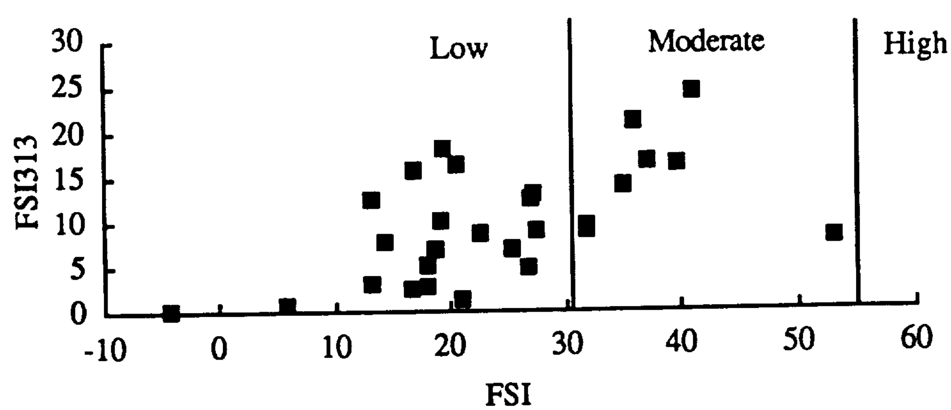


Figure 4.21. Calculated Values for FSI and FSI313 for 27 Events.

The regression analysis indicated a coefficient of determination (r^2, the ratio of explained variance to total variance) of 0.35 between the two indices which, based on the degrees of freedom (25), is a statistically significant correlation for $\alpha = 0.01$. The degree of correlation increased ($r^2 = 0.50$, statistically significant) if one outlier is removed from the analysis. The one outlier removed was from July 15, 1988 and was elevated because of wind speeds of 37 kts reported at 850 mbs. Based on this correlation, the FSI313 may prove to be a valuable forecast tool and further investigation is warranted. The two events with high FSI estimates were examined to determine the reason for the large FSI estimates. In both instances, strong winds at 850 mb level were responsible for the large FSI estimates. As stated earlier, one important outcome from this investigation is that significant fog can develop at TTS in the presence of strong winds at the 850 mb level. This is permitted by a decoupling of the surface and the planetary boundary layer winds as a strong temperature inversion develops.

Figure 4.22 shows the FSI estimates for the advection fog events. All estimates fell within the moderate to high probability categories and more than half the events had estimates in the high risk category. No events fell within the low probability area (i.e., greater than 55).

Figure 4.23 displays the FSI estimates for the pre-frontal events. These estimates also fall within the moderate to high risk category with 9 of the 12 events having a FSI less than 31 (i.e., high probability category). None of the pre-frontal fog events had FSI estimates greater than 55 (low risk).

Information on the fog precursors skill scores (false alarm) based on the 5 year TTS observations and Cape Canaveral AFS Rawinsondes is included in Section 6.2.

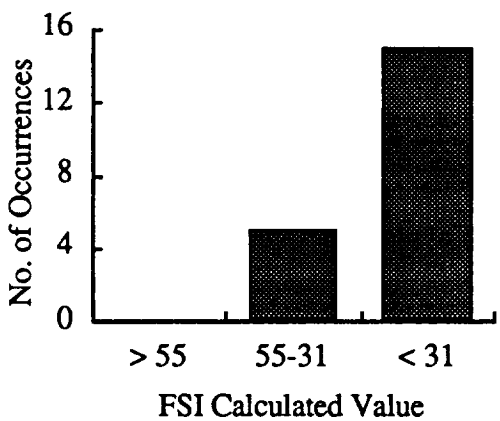


Figure 4.22. Fog Stability Index for Advection Events.

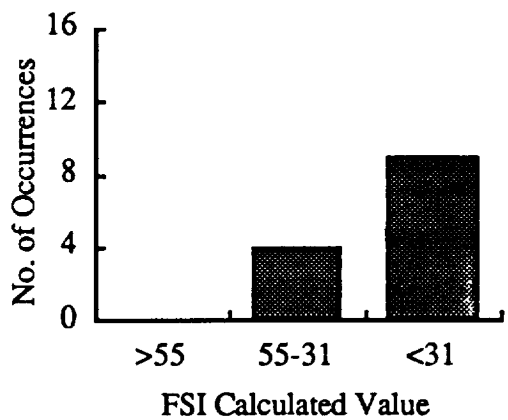


Figure 4.23. Fog Stability Index for Pre-Frontal Events.

5.0 Forecasting Tools

5.1 Meteorological Interactive Data Display System (MIDDS) McBasi Program

To facilitate the analysis of fog precursor information, a Man-computer Interactive Data Access System Basic (McBasi) language interface utility was developed on MIDDS. McBasi is a line oriented editor and on-line BASIC language interpreter within the mainframe McIDAS environment and in McIDAS-OS2 (PC level). This utility produces a 4-panel graphic screen (see Figure 5.1) that displays data from the local wind tower network, observations from DAB, MCO, COF, MLB, and TTS, and the FSI313.

Two of the panels present a time series of the wind direction from tower 1108 and from SLF tower 512. These panels give the forecaster a west-to-east view of the local tower data to monitor wind speed and direction. Panel 3 is a time series graph of relative humidity values from the 6, 54, 204 and 492 foot levels of tower 313. This graph allows the forecaster to monitor the depth of the moisture layer from the surface to 492 feet. Panel 4 is a time series graph of the temperature reported at tower 313 at the 6 and 492 foot levels. This graph allows the forecaster to monitor the strength of the low level inversion. On the top right of the screen is a tabular list of data from tower 313. It displays the current temperature, relative humidity, wind direction and wind speed from the 54, 204 and 492 foot levels. Centered on the bottom of the graphic screen is the FSI313, and in the center of the display are data from six surface observation stations in central Florida. The data from the surface stations include the lowest ceiling reported at the site, the lowest cloud deck that is not a ceiling, weather conditions, temperature, dewpoint, wind direction, and speed. On the top left of the display is the temperature difference between the surface and 1000 mb from the most recent CCAFS rawinsonde.

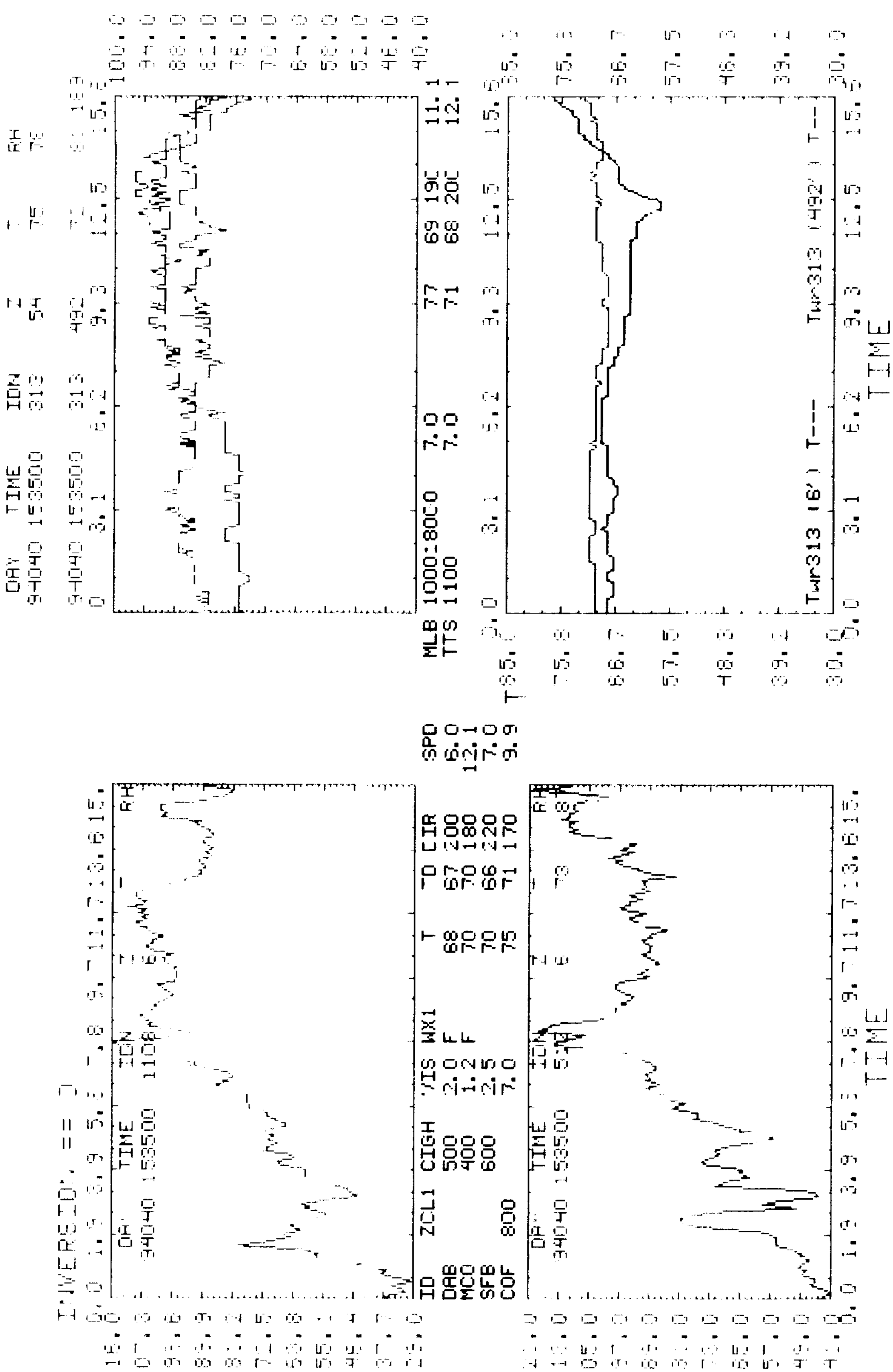


Figure 5.1. Example of the McBasi Fog Precursor Graphic Display.

Three MIDDS McBasi utilities were developed to calculate fog forecast indices. One McBasi program "FSI" (see Figure 5.2) calculates the FSI index using the current Cape rawinsonde. This utility uses the TTS surface observation along with the 850 mb data from the rawinsonde to calculate the FSI. The second McBasi utility, "FSI313" (see Figure 5.3) uses the TTS surface observation data along with the 492 foot data from tower 313 to calculate the FSI313. The program "FSI313" can be updated each hour to monitor trends in the FSI313. The third, FSINGM (see Figure 5.4) uses the NGM Point Analysis data to calculate a FSI out to the 48 hour forecast point. The utility uses sigma level 1 and 4 to calculate the FSI. Sigma level 1 (approximately 1014 mbs) is near the surface and sigma level 4 is near 850 mbs.

To compute the FSI, enter the command "FSI xx:xx" at a MIDDS terminal. The xx:xx is the Cape Canaveral rawinsonde file time. The output is to the VGA display screen and gives the calculated FSI estimate along with the FSI fog likelihood categories and values. To display the FSI313 using the data from tower 313 enter the command "FSI313".

To compute the FSI using the NGM Point analysis data run the McBasi program "FSINGM" at a MIDDS terminal. The output is to the VGA display screen and gives the calculated FSI estimate out to the 48 hour point. If the user wishes to change the output to a file or printer use the DEV=F or Dev=P options, respectively.

```
K-INDEX/1000-850 = -7.4
K-INDEX/SFC-1000 = -7
INVERSION = 21.1
          FSI    Likelihood of Radiation Fog
          >55              Low
          31-55          Moderate
           <31             High

FOG STABILITY INDEX (FSI) = -22.39
FSI(Twr313) Index = -41.6
```

Figure 5.2. Example of McBasi Program FSI output.

```
TIME == 1550
  T   SPD DIR
  75    6 253
*** EOF ***
          FSI313   Likelihood of Radiation Fog
          >26              Low
          15-26          Moderate
           <15             High

             FSI(Twr313) Index = -42
DAB SP 1226 M1 BKN 20 BKN 300 OVC 11/2F 0000/990/SFC VSBY 4
DAB SP 1201 M4 BKN 20 BKN 300 OVC 1F 2305/990/SFC VSBY 3
DAB SA 1152 1 SCT 20 SCT 300 -BKN 1/2F 123/67/67/2804/990/SFC VSBY 3/
     207 1508 20020 48167
DAB SP 1137 1 SCT 20 SCT 100 SCT E300 BKN 1/2F 2604/989/SFC VSBY 2
MCO SP 1235 M5 OVC 6F 2806/993
```

Figure 5.3. Example of McBasi Program FSI313 output.

```
Fcst Hour = 2000 Wind Dir = 42 FSI =>  21
Fcst Hour = 3000 Wind Dir = 107 FSI =>  25
Fcst Hour = 4000 Wind Dir = 125 FSI =>  30
Fcst Hour = 5000 Wind Dir = 116 FSI =>  28
Fcst Hour = 7000 Wind Dir = 18 FSI =>  36
Fcst Hour = 8000 Wind Dir = 69 FSI =>  35
Fcst Hour = 9000 Wind Dir = 94 FSI =>  36
Fcst Hour = 10000 Wind Dir = 102 FSI =>  37
Fcst Hour = 11000 Wind Dir = 108 FSI =>  34
Fcst Hour = 12000 Wind Dir = 122 FSI =>  33
Fcst Hour = 13000 Wind Dir = 128 FSI =>  31
Fcst Hour = 14000 Wind Dir = 129 FSI =>  26
Fcst Hour = 15000 Wind Dir = 135 FSI =>  26
Fcst Hour = 16000 Wind Dir = 138 FSI =>  27
Fcst Hour = 17000 Wind Dir = 142 FSI =>  27
Fcst Hour = 18000 Wind Dir = 149 FSI =>  28
Fcst Hour = 19000 Wind Dir = 157 FSI =>  28
Fcst Hour = 20000 Wind Dir = 164 FSI =>  27
Fcst Hour = 21000 Wind Dir = 175 FSI =>  25
Fcst Hour = 22000 Wind Dir = 176 FSI =>  24
Fcst Hour = 23000 Wind Dir = 168 FSI =>  26
Fcst Hour = 24000 Wind Dir = 169 FSI =>  26
Fcst Hour = 25000 Wind Dir = 186 FSI =>  21
Fcst Hour = 26000 Wind Dir = 218 FSI =>  19
Fcst Hour = 27000 Wind Dir = 215 FSI =>  21
Fcst Hour = 28000 Wind Dir = 186 FSI =>  25
Fcst Hour = 29000 Wind Dir = 173 FSI =>  28
Fcst Hour = 30000 Wind Dir = 166 FSI =>  34
Fcst Hour = 31000 Wind Dir = 163 FSI =>  37
Fcst Hour = 32000 Wind Dir = 164 FSI =>  39
Fcst Hour = 40000 Wind Dir = 219 FSI =>  38
Fcst Hour = 41000 Wind Dir = 223 FSI =>  38
Fcst Hour = 42000 Wind Dir = 228 FSI =>  36
Fcst Hour = 43000 Wind Dir = 239 FSI =>  34
Fcst Hour = 44000 Wind Dir = 252 FSI =>  31
Fcst Hour = 45000 Wind Dir = 262 FSI =>  30
DAY == 93322  TIME == 120000
For Fog Formation, Wind Direction needs to be between 150 - 330.
Calculated FSI        Risk of Formation
   > 51                  . Low
  31 - 51                 Moderate
   < 31                    HIGH
```

Figure 5.4. Example of McBasi Program FSINGM output.

5.2 Fog Forecasting Decision Trees

A series of decision trees were developed to help summarize a methodology for forecasting fog formation at TTS. These decision trees, which were included in the preliminary report (Wheeler, 1993), were used during several fog events during the past fog season and proved very helpful in determining the potential for fog development. After using the preliminary decision trees during this past fog season some minor modification to the decision trees were made. One of the modifications to the decision trees was to include an analysis of the relative humidity sensors at tower 313. Analyses have indicated the depth of the moisture layer is important to fog development at TTS.

In addition, a review of the output from the McBasi program "FSINGM" has been added to the decision trees. This program (discussed in Section 5) provides an estimate of the potential for fog development for a 48 hour forecast period.

Some of the individual parameters on the worksheets can be analyzed up to 48 hours in advance (FSINGM), but the majority will need to be examined in the early morning hours using the 2200-2300 UTC Cape Canaveral rawinsonde and current local observations. Key sensors (e.g. local tower wind data) will need to be monitored up to 2 hours before fog formation.

Step one of the decision tree process (Figure 31) will define the general conditions in the Cape Canaveral area and produce a fog likely or unlikely result which can be used by the forecaster as part of his/her decision making process. The decision tree process is a step-by-step process which the forecaster can use to help analyze the data to determine the potential for fog development at TTS, see Figures 5.2 through 5.6.

Key factors in forecasting fog at Cape Canaveral:

- Persistence - if fog occurred on the current day and the synoptic conditions have not changed significantly and are not expected to change, then fog will probably occur the next day.
- Moisture - for a fog event to occur, there must be significant low level moisture (at and below 900 mb).
- Atmospheric stability - the low levels of the atmosphere must be stable.
- Dry air aloft (except for pre-frontal fog events) - generally, there must be drier air aloft to allow for radiational cooling (above 850 mb).
- Westerly wind component - generally, the surface wind flow will be from 150° to 330°(monitor tower output display). In addition, the location of the surface ridge line is important. If the ridge is to the south of the Cape there is a better chance for westerly flow and fog formation.

All or most of these features must be present for rapid deterioration of visibility due to fog or stratus at TTS. Trend analysis and continuity of these features are important in understanding how fog develops and effects the TTS area. The worksheets are designed to help the forecaster monitor these features and trends prior to possible fog development in the TTS area.

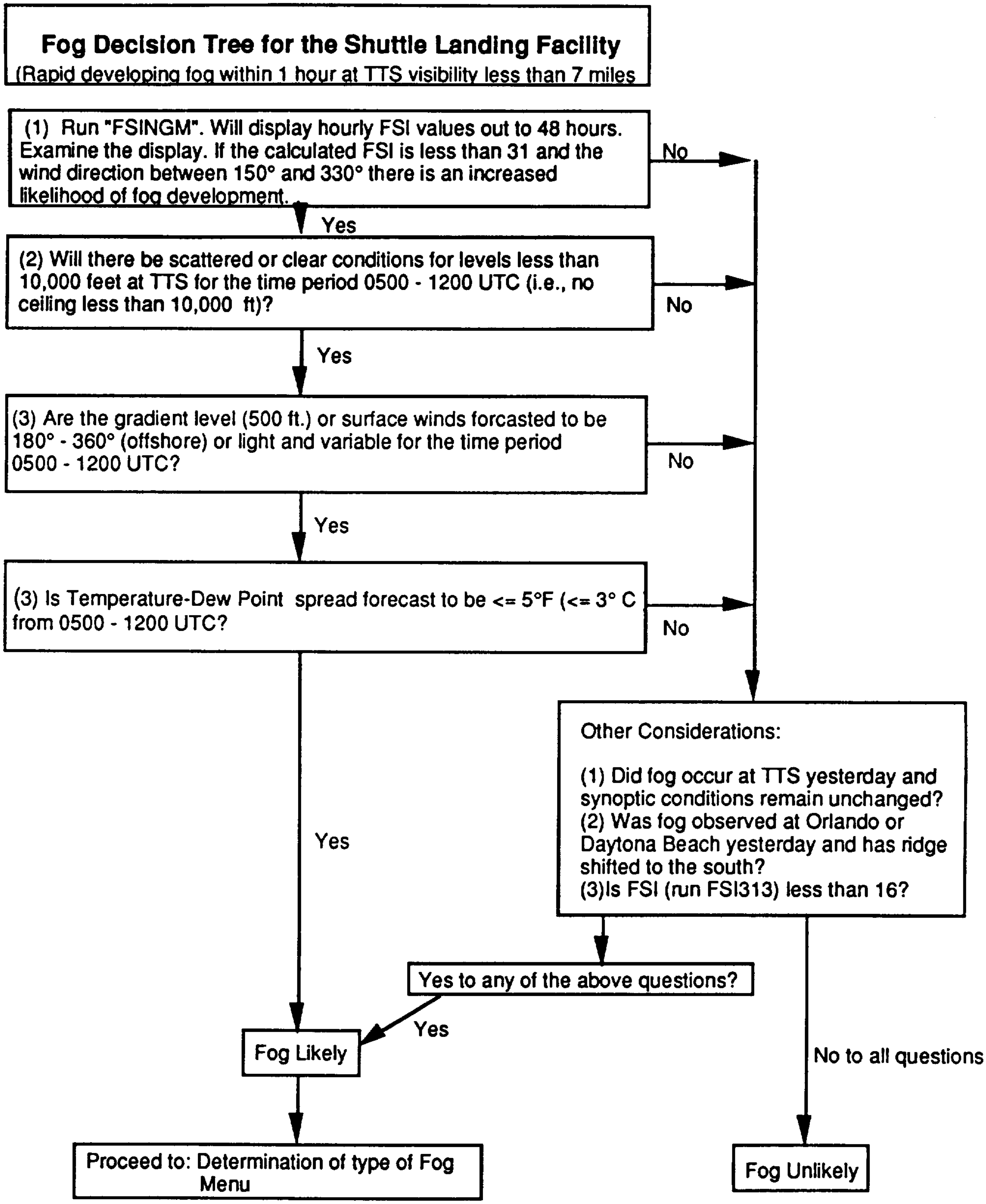


Figure 5.5. Step One of the Fog Decision Tree.

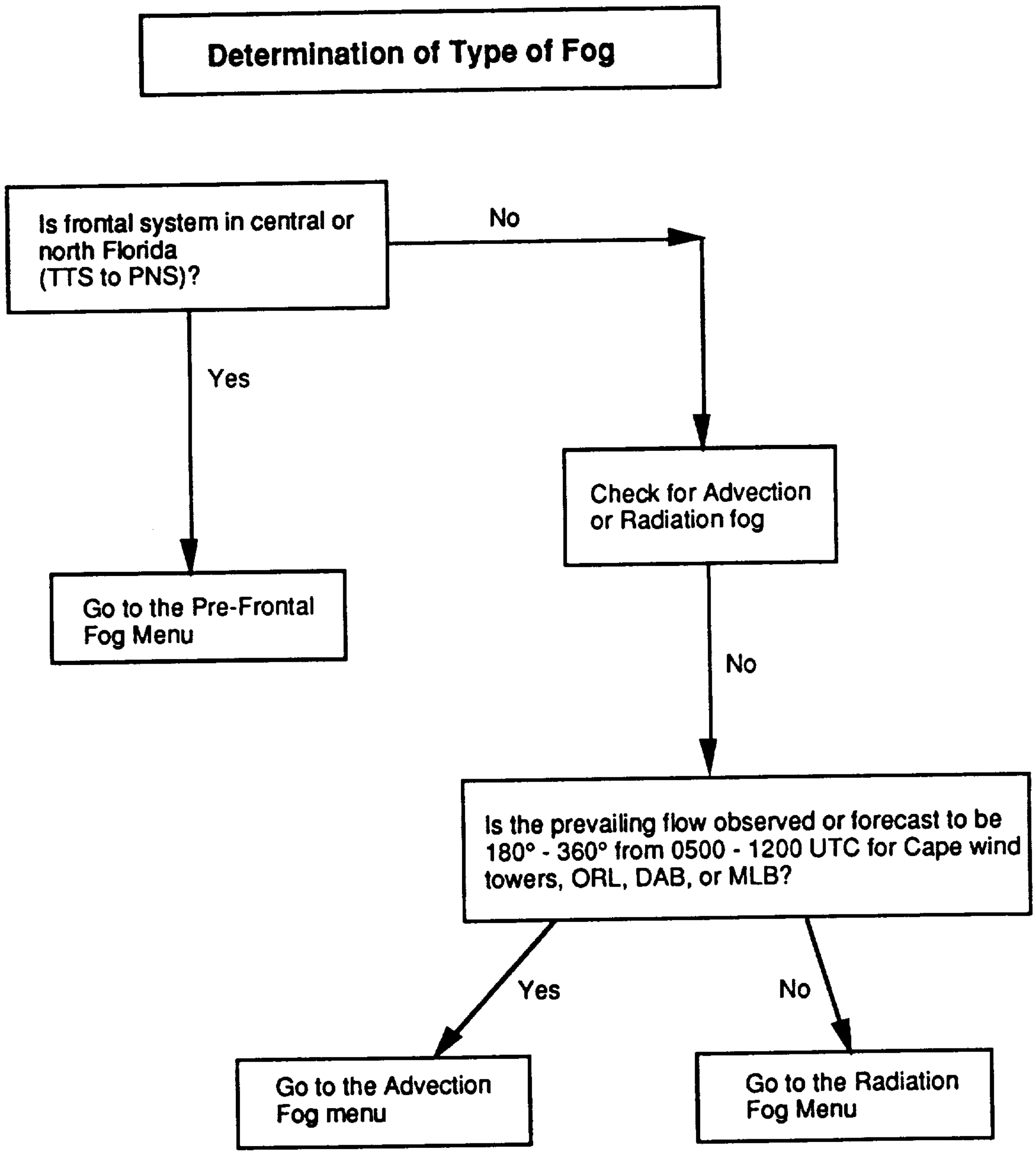


Figure 5.6. Step Two of the Fog Decision Tree (Type of Event).

Pre-Frontal Fog Menu

<u>Major Items to Check:</u>
(1) Was fog reported at TTS yesterday?
(2) Was fog reported at DAB or ORL yesterday?
(3) Will the surface ridge line be near or to the south of the Cape?
(4) Will the frontal system still be to the northwest of the Cape by sunrise (1100-1200 UTC)?
(5) Execute McBasi programs "FSIA" and FSI313". Yes/No

Yes

A Yes answer to one or more of these questions means a high likelihood of fog at TTS.

No

A No answer to all of the above questions indicates fog is not quite as likely, but conditions must continue to be monitored very closely.

<u>Key Items to check from the Fog Program:</u>
(1) Run "TWRFOG", example: "TWRFOG 10".
(2) Monitor wind tower data for a northwesterly shift. If this occurs, forecast fog occurrence at TTS within 1-2 hours.
(3) Monitor RH values at tower 313 (panel 2). RH >70% increase chance of fog.
(4) Continuously monitor surface observations at ORL, MCO, SFB, TIX, and DAB for stratus and fog development. If fog develops at any of these sites, forecast fog occurrence at TTS within the next 1-3 hour period.
(5) Check inversion strength on Cape soundings and between 6 and 492 feet on tower 313. Stronger inversions indicate a higher potential of fog occurrence.

<u>TTS Fog Climatology (Pre-Frontal Cases):</u>

Category (TTS)	Range	%
Fog Onset	0700 - 1100 UTC	62
	0900 - 1100 UTC	45
	Before 0700 UTC	23
Prevailing Wind Direction	180° - 360°	100
	240° - 300°	38
Wind Speed	> 5 knots	62
Fog Break-up Time	By 1600 UTC	85

Figure 5.7. Step Three of the Fog Decision Tree (Pre-Frontal Type)

Advection Fog Menu

Major Items to Check:
(1) Was fog reported at TTS yesterday?
(2) Was fog reported at DAB or ORL yesterday?
(3) Will the surface ridge line be near or to the south of the Cape?
(4) Execute McBasi programs "FSI" and FSI313". Yes/No

Yes

A Yes answer to one or more of these questions means a high likelihood of fog at TTS.

No

A No to all of the above questions indicates fog is not quite as likely, but conditions must continue to be monitored very closely.

Key Items to check from the Fog Program:
(1) Run "TWRFOG", example: "TWRFOG 10".
(2) Monitor wind tower data for a northwesterly shift. If this occurs, forecast fog occurrence at TTS within 1-2 hours.
(3) Monitor moisture depth (panel 2). Values greater than 70%, increases chance for fog.
(4) Continuously monitor all central Florida surface observations (ORL, MCO, SFB, TIX, and DAB) for stratus and fog development. If fog develops at any of these sites, forecast fog occurrence at TTS within the next 1-3 hour period.
(5) Monitor inversion strength on Cape soundings and between 6 and 492 feet on tower 313. Stronger inversions are more indicative of fog occurrence.

TTS Fog Climatology (Pre-Frontal Cases):

Category (TTS)	Range	%
Fog Onset	0700 - 1100 UTC	75
	0900 - 1100 UTC	50
Prevailing Wind Direction	180° - 360°	90
	240° - 300°	45
Wind Speed	> 5 knots	85
	< 5 knots	15
Fog Break-up Time	By 1600 UTC	85

Figure 5.8. Step Three of the Fog Decision Tree (Advection Type)

Radiation Fog Menu

Key Items to Monitor

(1) Monitor dewpoint depression on towers and at TTS. Look for depressions of less than 5°F (3°C). If spread less than 3°F (1°C) there is a good chance of fog at TTS.
(2) Look for light and variable winds of less than 3 knots.
(3) Surface ridge line must be very close to central Florida with very weak pressure gradient over the state (i.e., less than 1 mb) from JAX to MIA.
(4) Fog Susceptibility Index (FSI). Run McBasi programs "TWRFOG", "FSI" and "FSI313". Monitor Tower 313 RH values (panel 2).

	FSI
>55	Fog not likely
31-55	Fog possible
<31	Fog likely

(5) Inversion strength on the Cape and Tampa rawinsondes, and between 6 and 492 feet on tower 313.
(6) Fog onset is generally occurs after 0700 UTC and more likely near sunrise.

Figure 5.9. Step Three of the Fog Decision Tree (Radiation Type)

6.0 Fog Precursors

6.1 Fog Precursor Elements

Development of fog in central Florida is associated with several precursors. These precursors can be identified and used to help forecast fog occurrence. The following is a list of precursors associated with the three basic fog types. These precursors are also listed on the prefrontal, advection, and radiation fog decision trees.

- Persistence is an excellent forecasting tool. If fog occurred at TTS the previous morning and no significant change is seen in the synoptic features, then fog is likely for the next day.

Advection fog development:

- Small surface dew point depression (0° - 5° F, (0° - 3° C)) is important.
- Fog forms west of the TTS area first (up to two hours prior to development at the TTS). The surface observations from Daytona Beach and Orlando from 0000 UTC through the morning hours can be monitored for fog development.
- Location of the surface ridge axis is crucial in determining the surface wind flow. If the ridge axis is south of Cape Canaveral, this increases the chances for fog development. If the ridge is north and forecasted to stay north, fog development is unlikely although there may be patchy ground fog.
- Time series analysis of tower reports is necessary to determine land breeze flow conditions. The McBasi program "TWRFOG" can be used to monitor the wind flow. A westerly wind component increases the chance for fog formation. The wind tower data may show a double shift to a more westerly component (see Figure 5.1). Fog formation often occurs within 30 minutes after the second shift.
- Low-level moisture combined with dry air aloft is important for fog formation. If the lower atmosphere is moist but dries rapidly above 850 mb, fog can occur. If the sounding is moist up to 700 mb, fog is unlikely since this limits the radiational cooling. The McBasi program "TWRFOG" can be used to monitor the low level moisture content.
- The strength of the low level inversion is directly proportional to the likelihood of fog development. The McBasi program "TWRFOG" can be used to monitor the 6 to 492 foot temperature inversion at tower 313.

Pre-Frontal fog development:

- If a frontal boundary exists from the Florida panhandle to the Cape and is forecast to pass the TTS area in the next 24 hours, then pre-frontal fog development is possible.
- Small surface dew point depression (0° - 5° F, (0° to 3° C)) is important for fog development.
- If fog forms from Daytona Beach to Orlando, the probability of fog at TTS is increased.

- A shift in the wind direction to a more west or northwest direction increases the probability of fog formation at TTS. The McBasi program "TWRFOG" can be used to monitor the local wind flow.

- A low level temperature inversion is required for fog formation. The McBasi program "TWRFOG" allows the forecaster to monitor the inversion from 6 - 492 feet at tower 313.

Radiation fog development:

- Generally, fog development occurs near sunrise.

- Low level moisture (dew point depression of 3°C (5°F) or less) up to 900 mb and drier air (dew point depression of 5°C (9°F) or more) above 850 mb is necessary for fog formation. The McBasi program "TWRFOG" can be used to monitor the low level moisture content.

- Surface winds are generally calm or have a weak southwest to northwest component (3 knots or less).

- A westerly shift in the low level wind flow increases moisture advection and increases the probability of fog. The McBasi program "TWRFOG" can be used to monitor the wind flow.

6.2 Fog Precursors Skill Scores

The 5 year TTS observation and Cape rawinsonde data bases were used to determine the Probability of Detection (POD) and the False Alarm Rate (FAR) for key fog precursors. This multi-step process was used to determine a yes or no condition based on certain criteria.

The data used in this analysis contain the 36 case study fog events and 222 no fog events extracted from the 5 year SLF data base. The no fog event days satisfy the surface based fog precursor criteria listed below.

- TTS reported offshore surface wind flow (i.e. wind reported 150° to 330°).
- TTS reported surface dew point depression less than 5° F (3° C).

The no fog event days were examined to determine if one or more of the criteria listed below were satisfied. These criteria are the inverses of the upper air precursor criteria identified in the previous section. Satisfying of one or more of these criteria reduces the likelihood of fog development.

1) Lack of 1000 mb moisture (i.e. 1000 mb $T\text{-}T_d$ spread greater than 3° C, (5° F)).
2) 1000 mb wind onshore (i.e. 1000 mb wind direction between 330° and 150°).
3) 1000 mb Wind Speed > 20 kt.
4) FSI > 31.

If one or more of the four criteria were satisfied, then the forecast was for no fog. If none of the four criteria were satisfied, then the forecast was for fog to develop.

The following skill scores were computed from the data in Table 6.1. The following scores were based on a forecast for fog.

- Probability of Detection (POD) 78%
- False Alarm Ratio (FAR) 45%
- Failure to Detect 23%

Table 6.1. Precursor Contingency Table

	No Fog Occurred (No)	Fog Occurred (Yes)
Conditions 1, 2, 3, or 4 Occurred (NO Fog Forecast)	199	8
Conditions 1, 2, 3, and 4 Did Not Occur (YES Fog Forecast)	23	28

These false alarm ratios are good considering that the no fog event days satisfied the surfaced based fog precursor criteria (i.e., potential for fog development existed). In addition, not all fog precursors were included in the POD and FAR analysis because time constraints prohibited a detailed analysis of each of the 222 no fog events (e.g., determination of where fog first formed and location of the surface ridge). Furthermore, the high probability of detection indicates the upper air precursor criteria are effective in indicating days with a high likelihood of fog development.

7.0 Summary and Recommendations

The purpose of the study was to enhance the weather community's understanding of the precursors responsible for the fog development at the SLF and to develop tools to improve fog forecasting skill in support of the Space Shuttle Program, primarily for the de-orbit decision, which must be made up to 90 minutes prior to landing. For this investigation, the fog season was defined as beginning October 1 and ending April 30. The study focused on fog events at TTS which were characterized by rapid deterioration of visibility within a one hour period.

Following are a summary of key results, a brief description of the tools produced to assist the forecasters in evaluating the potential for fog development, and recommendations for additional sensors to improve detection of conditions indicative of subsequent fog development.

7.1 Summary of Results

The data analyzed cover a five year period from 1986 to 1990. All fog events within the period were identified, and the onset and dissipation times were determined for each fog event. In addition, a detailed analysis was performed on 36 TTS fog events characterized by rapid deterioration of visibility. As part of that analysis the fog events were categorized as either advection, pre-frontal or radiation.

The following identifies precursors categorization for each fog type.

Advection fog development:

- Small surface dew point depression (0° - 5° F, (0° - 3°C)) is important.
- Fog forms west of the TTS area first (up to two hours prior to development at the TTS).
- Location of the surface ridge axis is crucial in determining the surface wind flow. If the ridge axis is south of Cape Canaveral, chances for fog development increases.
- Time series analysis of tower reports is necessary to determine land breeze flow conditions. A westerly wind component increases the chance for fog formation.
- Low-level moisture combined with dry air aloft is important for fog formation. If the lower atmosphere is moist but dries rapidly above 850 mb, fog can occur. If the sounding is moist up to 700 mb, fog is unlikely since this limits the radiational cooling.
- The strength of the low level inversion is directly proportional to the likelihood of fog development. Monitor the 6 to 492 foot temperature inversion at tower 313.

Pre-Frontal fog development:

- If a frontal boundary exists from the Florida panhandle to the Cape and is forecast to pass the TTS area in the next 24 hours, then pre-frontal fog development is possible.
- Small surface dew point depression (0° - 5°F, (0° - 3°C)) is important for fog development.

- If fog forms from Daytona Beach to Orlando, the probability of fog at TTS is increased.
- A shift in the wind direction to a more west or northwest direction increases the probability of fog formation at TTS.
- A low level temperature inversion is required for fog formation. Monitor the inversion from 6 - 492 feet at tower 313.

Radiation fog development:

- Generally, fog develops near sunrise.
- Low level moisture (dew point depression of 5°F (3°C) or less) up to 900 mb and drier air (dew point depression of 5°F (3°C) or more) above 850 mb is necessary for fog formation. Monitor the 6 - 492 foot relative humidity values from tower 313.
- Surface winds are generally calm or have a weak westerly component (3 knots or less).
- A westerly shift in the low level wind flow increases moisture advection and increases the probability of fog.

Key results from the analyses performed in this study are:

- Many precursors associated with fog development such as low level inversion, local tower wind flow at the 54 foot level (westerly flow), and low level moisture (up to 300 feet) can be monitored using existing sensor networks.
- Using decision trees and utilities for monitoring key elements of the local data sets, the forecaster can monitor environmental conditions and forecast the likelihood of visibility restrictions due to fog or stratus.
- A high number (92%) of the fog events analyzed show a westerly component to the surface wind. In many events, a westerly shift in the winds is apparent in the wind tower data prior to the fog development.
- For the advection and pre-frontal events, 83% of the events had fog develop in the Orlando to Daytona Beach area up to 2 hours prior to development at TTS.
- The primary onset time for fog development at TTS is between 0700 to 1200 UTC. Almost 95% of all fog events had dissipated (visibility improved to 5 miles or greater) by 1600 UTC and 75% of the cases improved by 1400 UTC.
- A low level inversion at or below 500 feet is generally present.
- Fog can develop even in the presence of strong winds at 492 feet above the surface. In these cases, the top of the inversion would be below 500 feet.
- The vast majority of the rapid visibility deterioration events occurring between 1986 and 1990 were either pre-frontal or advection fog events. Only two of the events were associated with radiational cooling.

7.2 Conclusion

The purpose of this task was to develop data bases, analyses, and techniques leading to the improvement of the 90-minute forecasts made for Space Shuttle Program (SSP) landing facilities in the continental United States. The sub task addressed in this report concerns fog development that would affect the less than 7-statute mile visibility rule for End-Of-Mission (EOM) Shuttle landings at Kennedy Space Center (KSC). This rule was designed to protect against a visibility restriction of less than 7 miles developing unexpectedly within the next 90 minutes (i.e., after the de-orbit burn decision and before landing). In order to define the precursors and tools used in forecasting for fog at KSC, the Applied Meteorology Unit (AMU) developed an extensive database of surface and upper air weather parameters at the Shuttle Landing Facility (TTS) and throughout central Florida. As a result of these analyses, the AMU developed an extensive fog climatology database, forecaster fog decision trees, a fog stability index, and defined the key fog precursors needed for fog development, fog forecasting and advection into KSC.

The fog climatological analysis indicates that during the fog season there is higher risk for a visibility violation at KSC during the early morning hours (0700 to 1200 UTC), while 95% of all fog events have dissipated by 1600 UTC. A high number of fog events are characterized by a westerly component to the surface wind at KSC (92%) and that 83% of the fog events had fog develop west of KSC first (up to 2 hours) as reported at Orlando and Daytona Beach.

A major goal of the study was to identify fog precursors that could be used up to 12 hours in advance. To address this the AMU developed fog decision trees and forecaster tools and utilities. Using the decision trees as process tools ensures the important meteorological data are not overlooked in the forecast process. Using the tools and utilities, key fog precursors can be monitored and evaluated. Using the FSI313 utility a trend can be noted in the fog susceptibility index. By monitoring the FSINGM output a fog forecast can be made out to 48 hours. Then by monitoring the low level precursors using the TWRFOG utility developed by the AMU, the forecaster can monitor and observe the trends in the 54 foot local tower wind flow (westerly flow increase chance for fog formation), the low level inversion from 6 to 492 feet (the stronger the inversion the better the chance for fog formation), the relative humidity values at tower 313 from 54 to 492 feet (relative humidity reading at or above 70% are needed for fog formation at KSC), and finally the local observations can be monitored for fog formation west of KSC.

With these tools and a better understanding of fog formation in the local KSC area, the Shuttle weather support forecasters should be able to give the Launch and Flight Directors a better KSC fog forecast with more confidence.

7.3 Transition Utilities to Operational Use

The MIDDS utilities along with the Fog Forecasting Decision Trees require transition to operational use. For the RWO, these commands will be incorporated in their existing MIDDS F-Key menu systems. An example of these add on menus will be forwarded to SMG and the Melbourne NWS office for their use. The AMU will help in implementing the menus if necessary. Also, the AMU briefed the SMG forecasters on the content of this report and hopes to brief the RWO forecasters by May 1994.

7.4 Upgrade MESONET Wind Towers

The majority of the fog events analyzed indicate fog or stratus is advected in from the southwest, west or northwest. That area, the St. Johns River basin, is an excellent breeding ground for fog due to its marshy inland location. As of December 1993, the instrumentation west of the Banana River to the St. Johns River basin was limited to 15 wind towers (Figure 3.2) with wind direction and speed sensors located at the 54 foot level. Currently, the wind system is being upgraded and instrumentation to measure temperature, dew point, and relative humidity has been added to most of the towers.

In addition to the ongoing tower system upgrade, installing visibility sensors at several sites west of the Banana River from the southwest to northwest would be beneficial. Possible locations of these sensors could be towers 0819, 2016, 2202, and 1000. A site survey would be needed before exact sites are chosen for the visibility sensors. These sensors would provide the SMG and RWO forecasters real-time information on visibility conditions west of the SLF. This information would allow the forecaster to detect fog development over the St. Johns River valley and improve fog forecasting skill in support of Shuttle operations. Another option would be to install at least one and possibly two Automatic Surface Observing Sites (ASOS) in the St. Johns River basin area. This option would provide the forecaster all the above data plus cloud definition information.

8.0 References

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NASA Johnson Space Flight Center and Marshall Space Flight Center, 1988: *Shuttle Flight Rule Workshop on Fog*.

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APPENDIX A: Case Studies

This Appendix contains information on two case studies of two fog events, one categorized as advection and one as pre-frontal are presented. The advection fog event occurred on 21 January 1990. The pre-frontal fog event occurred on 8 February 1989. Both events had several precursors indicating the likelihood of fog development at TTS.

A.1 Advection Case

January 20-22 1990 Case Study

Synoptic Analysis

At 1200 UTC on 20 January 1990, the major synoptic features over the eastern United States included a low pressure system over northeast Nebraska with a trailing cold front south across Missouri, Western Tennessee, Mississippi, extending southward into the Gulf of Mexico (see Figure A-1). A warm front extended from this low across Kentucky to South Carolina and into the Atlantic Ocean. A weak high pressure ridge was located over northern Florida. This ridge was providing central and south Florida with a moist low-level southeasterly flow. At 500 and 700 mbs the ridge was to the south of the Cape Canaveral area which provided southwest flow at those levels. Over the northern sections of Florida, the flow was from the south and southwest from the surface up to 500 mb. During the early morning hours of 20 January, weather conditions varied considerably over the central sections of Florida. To the west and north of Cape Canaveral, winds were weaker thus limiting low-level mixing and resulting in more significant fog formation. Both Daytona Beach and Orlando reported dense fog for several hours prior to and near sunrise. Winds at both of these sites were 2 to 3 knots with temperatures in the 60-65°F range. Between 0600 and 0900 UTC fog was forming from Orlando to Daytona Beach. By 1200 UTC, some fog was reported at Titusville with visibility reduced to 4 miles. At TTS patchy ground fog was reported from 0700 to 1300 UTC, but the visibility never dropped below 9 miles. In addition, areas to the south of KSC (i.e., Melbourne, Vero Beach, Patrick AFB) remained basically clear with no fog or low level stratus. During the afternoon of 20 January, winds continued to be from the southeast at 8-15 kts with some gusts to 20 knots along the coast. Temperatures were near 80°F along the coast to the mid-80s in the Orlando area with dew points remaining in the 60s.

During the afternoon of 20 January and early on 21 January the low-level surface pressure ridge shifted to south Florida. As shown in Figure A-2, at 1200 UTC on 21 January the surface ridge was located over south Florida with a cold front moving into the western panhandle of the state. Most areas of north and central Florida ahead of the cold front experienced southwesterly low-level wind flow with widespread low stratus and fog conditions. Temperatures and dew points at this time were in the mid 60s.

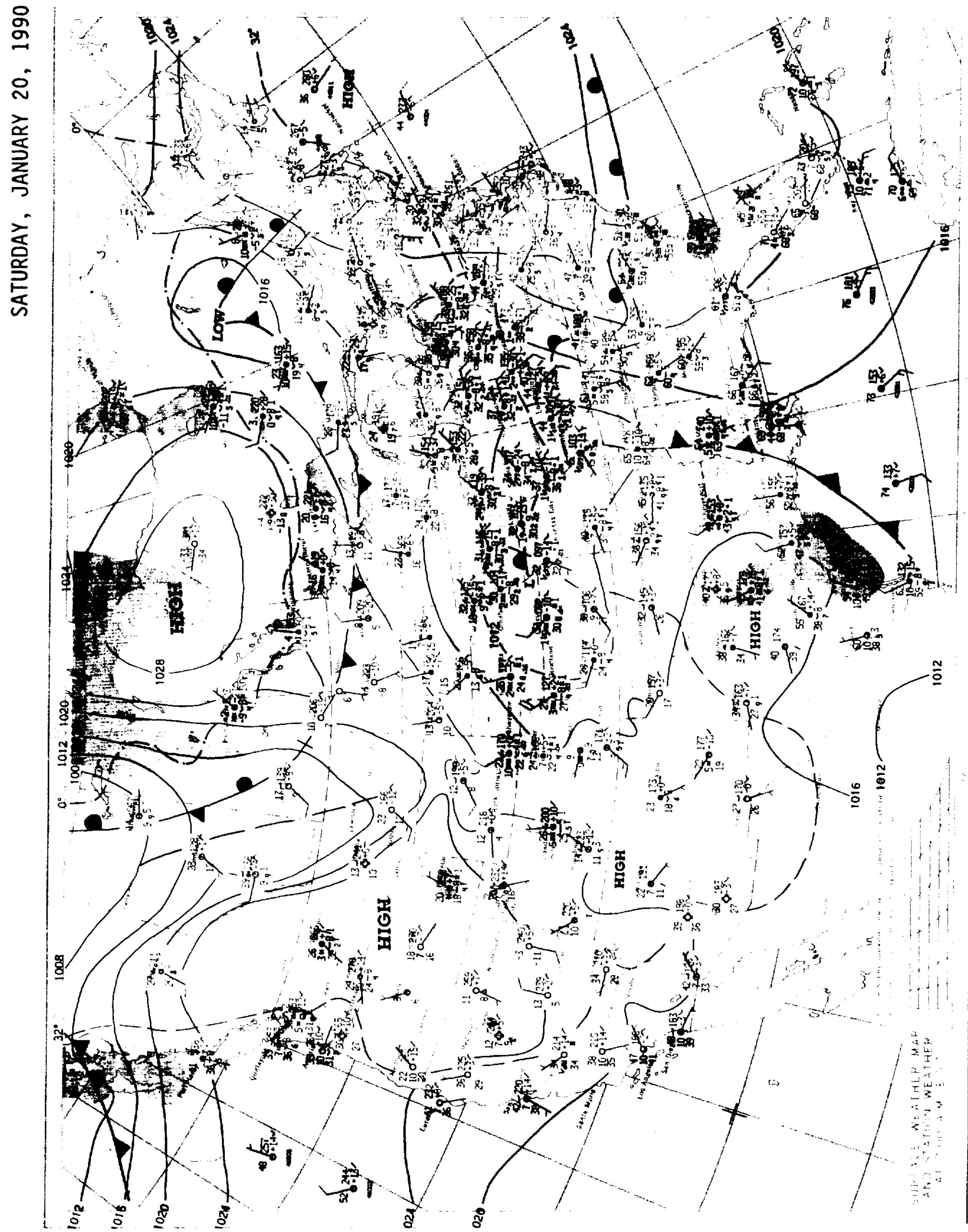


Figure A-1. Surface Analysis for 20 January 1990 at 1200 UTC.

Mesoscale Analysis

The low-level wind structure prevented fog formation at TTS on 20 January. As shown by the CCAFS sounding at 1115 UTC (Figure A-3), the low-level winds (1000 mb) were from the southeast at 15 knots. This southeast flow kept the lower boundary layer warmer with enough mixing to prevent fog formation near the coast from KSC southward. Sunrise temperatures at several of the coastal towers were in the upper 60s (°F) with wind speeds of 5-7 knots.

Weather conditions were quite different at TTS on 21 January compared to 20 January. As the low-level surface ridge shifted southward the winds turned more to the south and eventually southwest and west. This change in wind flow is quite evident from the 21 January 1115 UTC CCAFS sounding (Figure A-4). In addition, the low-level inversion on 21 January was approximately twice as strong as the 20 January inversion. On 20 January the inversion was 20 mb deep with a +3°C increase in temperature from bottom to top, while on 21 January the inversion was 10 mb deep with a +5°C increase in temperature to the top of the inversion. On 21 January fog formed at Orlando at 0800 UTC, at Daytona Beach at 0830 UTC, and at TTS at 0916 UTC. The low-level winds shifted from a south-southwest component to more westerly around 0900 UTC (see Figure A-5). Simultaneously, temperatures dropped and the temperature-dew point spread decreased. This shift to a westerly wind advected cooler and more saturated air from the mainland resulting in fog formation at TTS. The westerly wind also may have been associated with the advection of thicker fog and stratus from the St. Johns River valley.

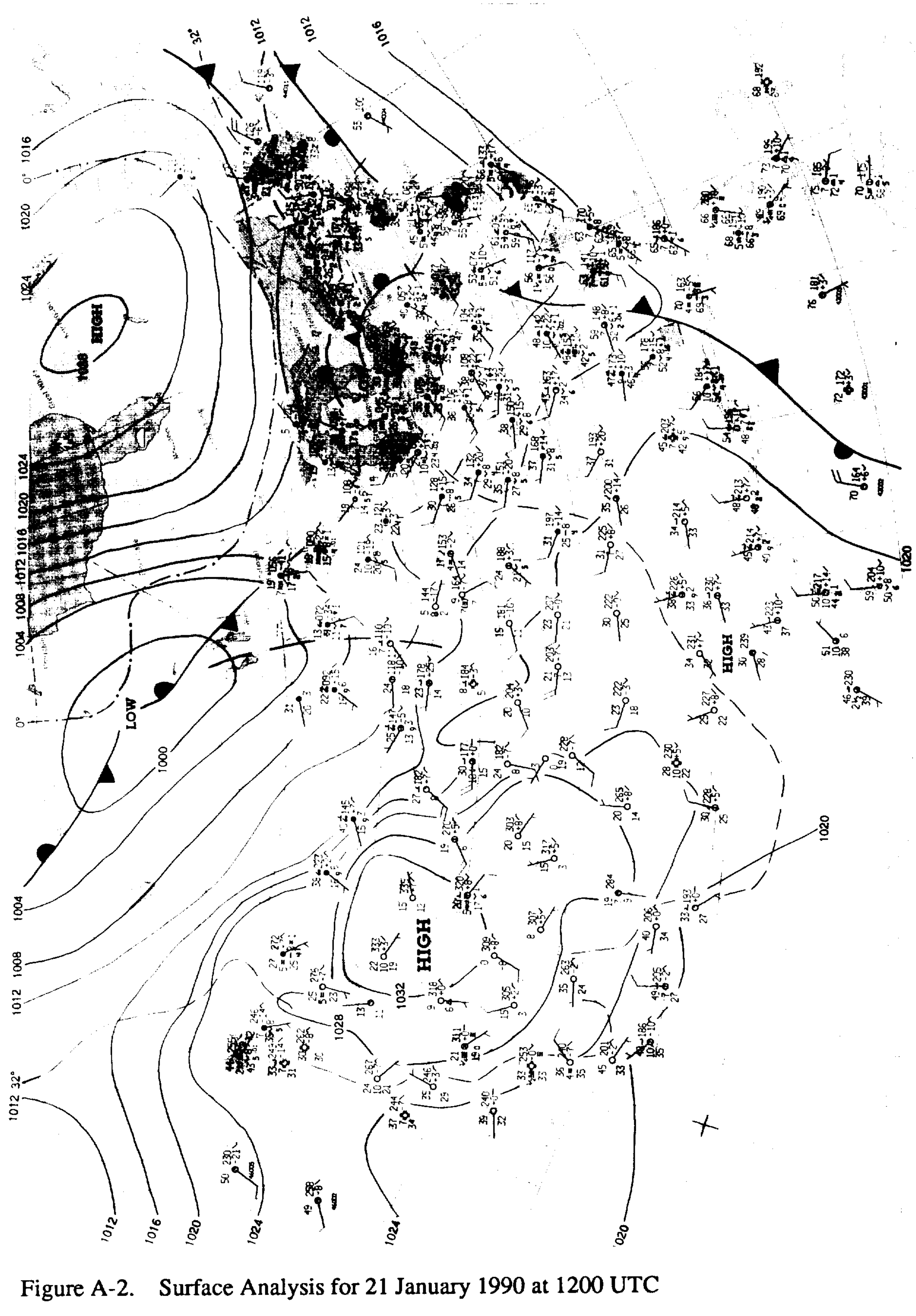


Figure A-2. Surface Analysis for 21 January 1990 at 1200 UTC

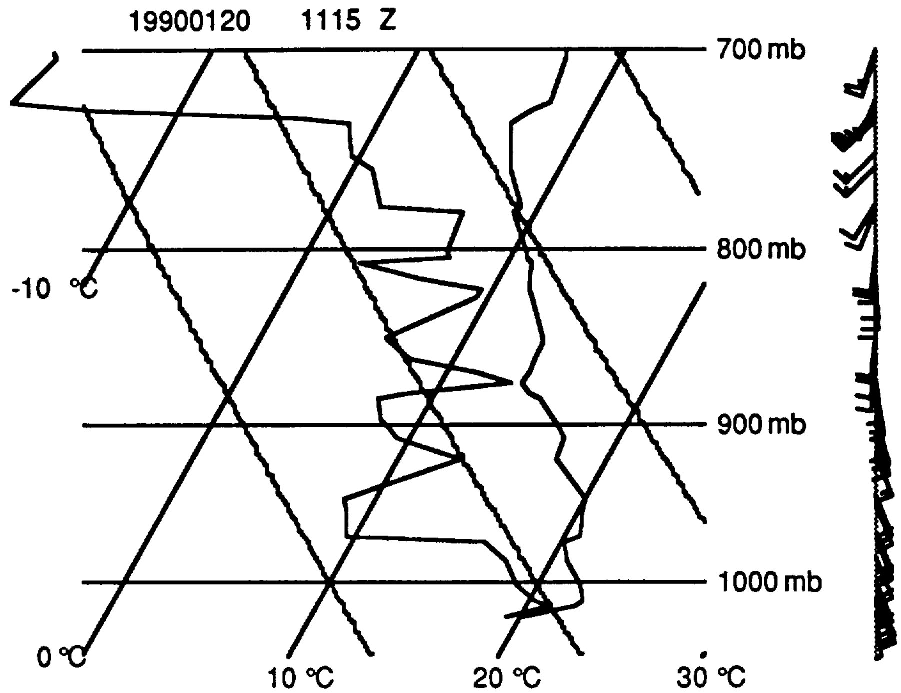


Figure A-3. CCAFS Sounding at 1115 UTC on 20 January 1990

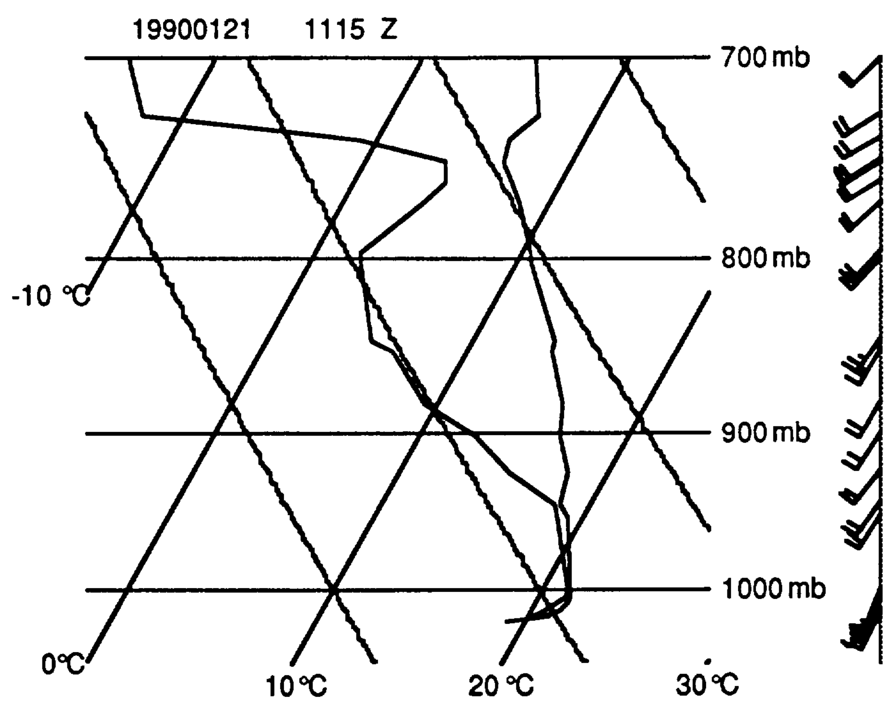


Figure A-4. CCAFS Sounding at 1115 UTC on 21 January 1990

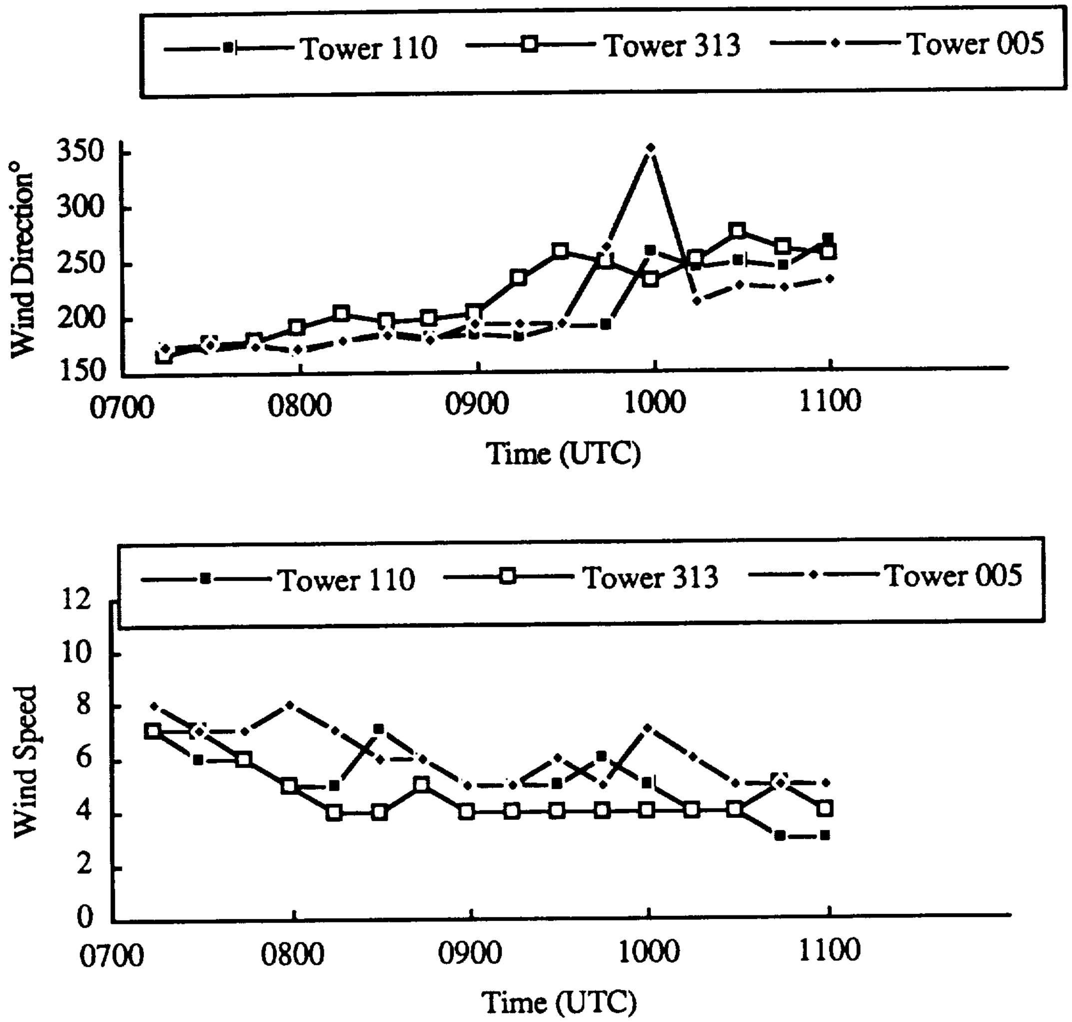


Figure A-5. CCAFS 54 ft Wind Tower Data for 0700 - 1100 UTC on 21 January 1990, See Figure 2 for Tower Locations.

Key Points (Precursors) from the Analysis of 20-22 January 1990:

- Low-level surface ridge shifted southward across Florida during 20-21 January 1990. This caused a shift in low-level winds at TTS from the southeast on 20 January to southwest on 21 January. This could have been detected by a 3-hourly synoptic analysis of Florida surface observations.

- Fog occurred inland around Orlando and to the north at Daytona Beach on 20 January. As the ridge shifted to the south of TTS during the next 24 hours, it was apparent that a shift to more of an offshore westerly wind component could advect fog over the KSC area on 21 January.

- Fog formation on 21 January was related to the shift to westerly winds advecting cooler more saturated air from the St. Johns River basin. This westerly wind may have been associated with the advection of fog and stratus from the mainland areas. The shift to westerly winds was apparent in the WINDS tower network.

A.2 Pre-Frontal Case

February 7-9 1989 Case Study

Synoptic Analysis

At 1200 UTC on 7 February 1989 (Figure A-6), the major synoptic features over the eastern United States included a low pressure system over the Tennessee/North Carolina border with a cold front trailing across central Georgia into the Florida Panhandle near Panama City then into the central Gulf of Mexico. A high pressure cell was centered over Texas. A high pressure ridge was located over Florida up through 500 mb. As shown by the 1030 UTC CCAFS sounding on 7 February (Figure A-7), this ridge was providing the Cape region with a west to southwesterly surface flow pattern at 10-20 knots. Significant moisture was present up to 850 mb with drier air aloft. During the early morning hours on 7 February, temperature and dew points over central Florida were generally in the low to mid 60s (°F) with patchy fog over inland areas. Surface winds in the early morning were southwesterly at 1-3 knots. By afternoon, temperatures had risen into the low to mid 80s (°F) with dew points in the mid 60s (°F). Winds were southwesterly at 5-10 knots, but by late afternoon a weak sea breeze developed along coastal sections.

By early on 8 February (Figure A-8), the cold front continued to move to the southeast and was located from the North Carolina/South Carolina shoreline to just south of Jacksonville to Cross City, Florida and into the Gulf of Mexico. With the approach of the frontal system, the low-level winds over central Florida became more westerly at speeds of 5 knots. Winds aloft continued to be west to southwest at 10-20 knots. Fog was widespread over the state north of a Tampa Bay-Vero Beach line. Visibility in many sections of central Florida was reduced to 1/4 mile or less with low stratus ceilings and even drizzle reported at several stations. Temperatures and dew points were generally in the low to mid 60s (°F). The fog and stratus lifted around 1700 UTC with temperatures rising into the upper 70s to near 80°F. The cold front continued to move slowly southward during the afternoon passing the Cape Canaveral region at approximately 2000 UTC. Winds prior to frontal passage were generally westerly at 5 knots, but then became northerly at 10 knots after frontal passage.

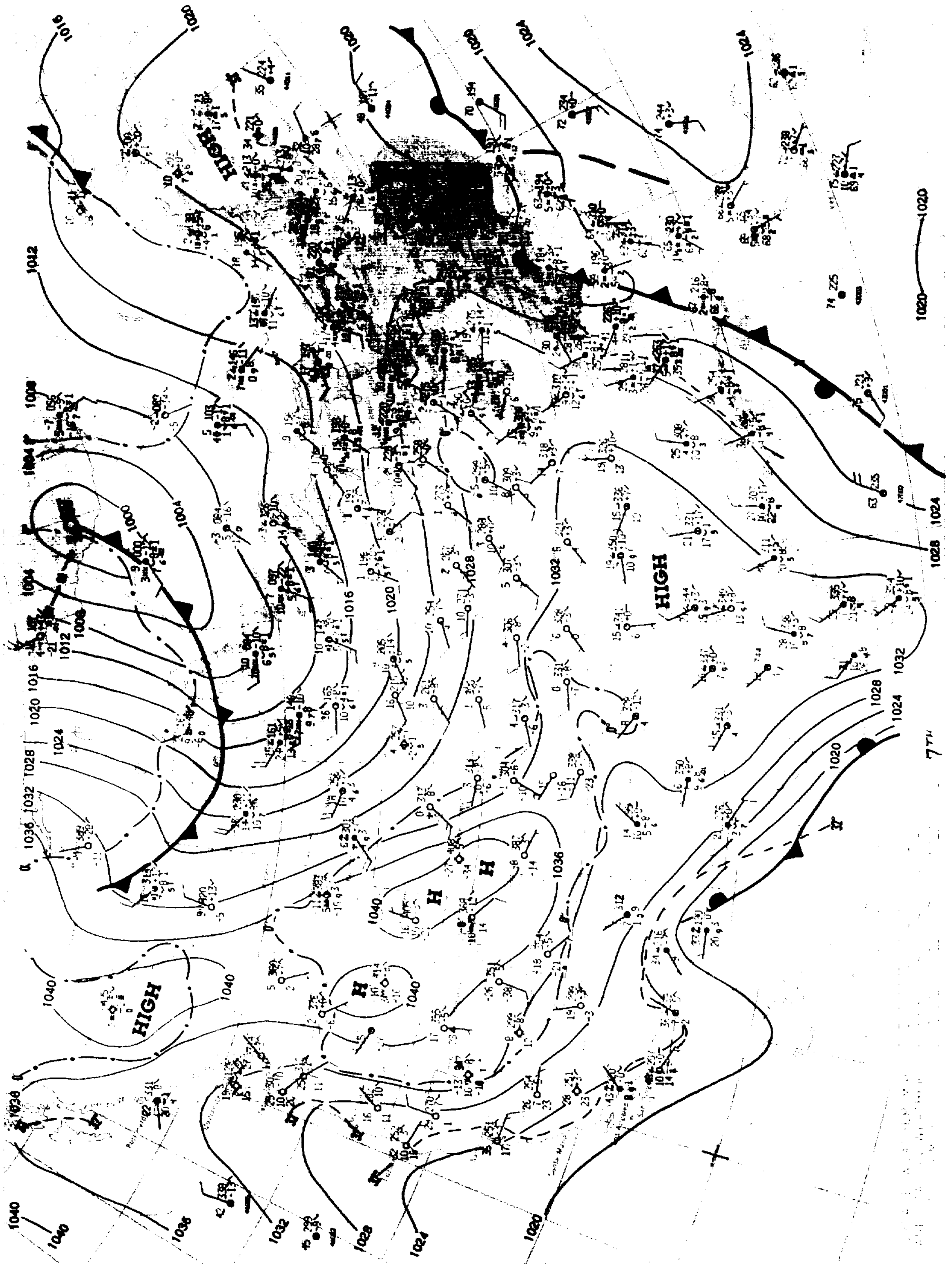


Figure A-6 Surface Analysis on 7 February 1989 at 1200 UTC.

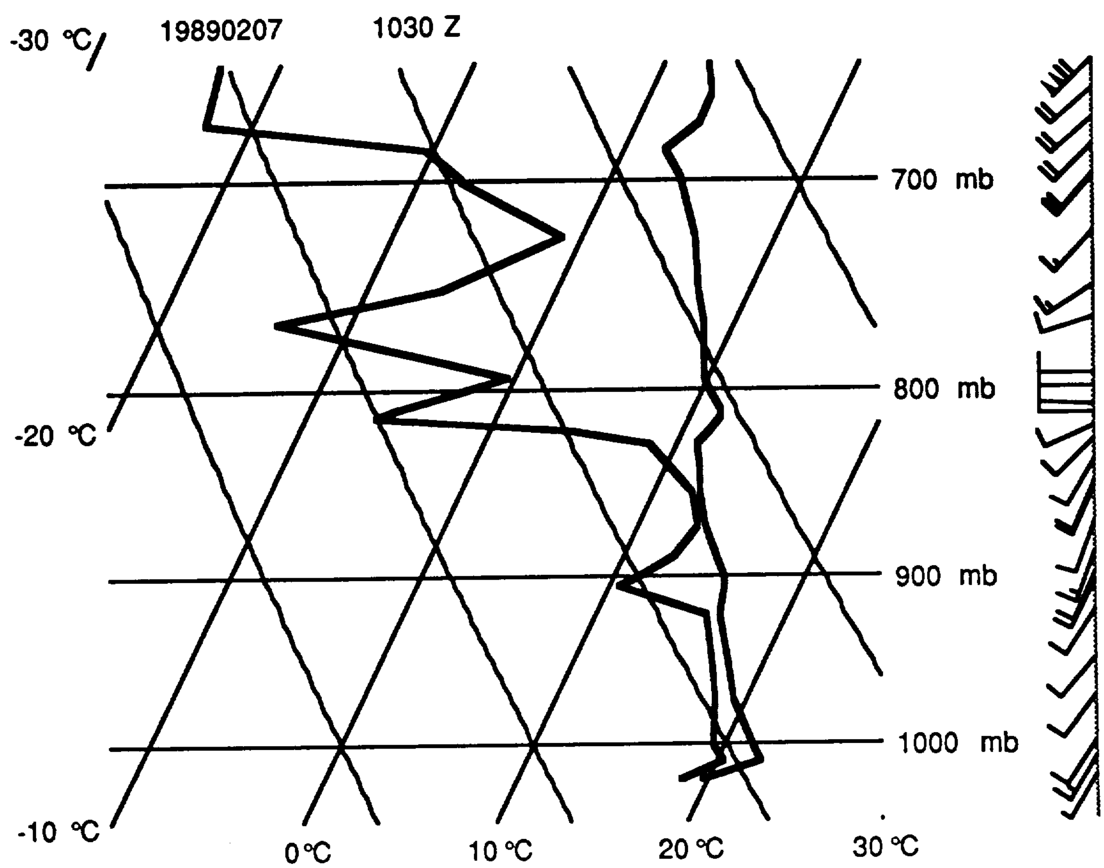


Figure A-7. CCAFS Sounding at 1030 UTC on 7 February 1989.

Mesoscale Analysis

On the morning of 7 February the low-level flow over Cape Canaveral region was south to southwesterly at 5-10 knots. Temperatures and dew points were in the mid 60s (°F). Only patchy ground fog was reported at TTS (0800 to 1000 UTC) and at several other inland stations during the early morning hours. However, Avon Park (AGR) did report significant fog with visibility down to 3 miles or less between 1130 and 1300 UTC. The early morning CCAFS sounding (Figure A-7) showed a 4°C surface based inversion with moist conditions up to 850 mb and considerable drying aloft. Winds just above the surface (1000 mb) were south-southwest 10-15 knots. The Cape Canaveral wind towers reported south to southwest winds at 5-10 knots (see Figure A-9) with no indication of a westerly wind shift throughout most of the night. This stronger south to southwesterly wind flow probably prevented fog formation during the early morning hours on 7 February.

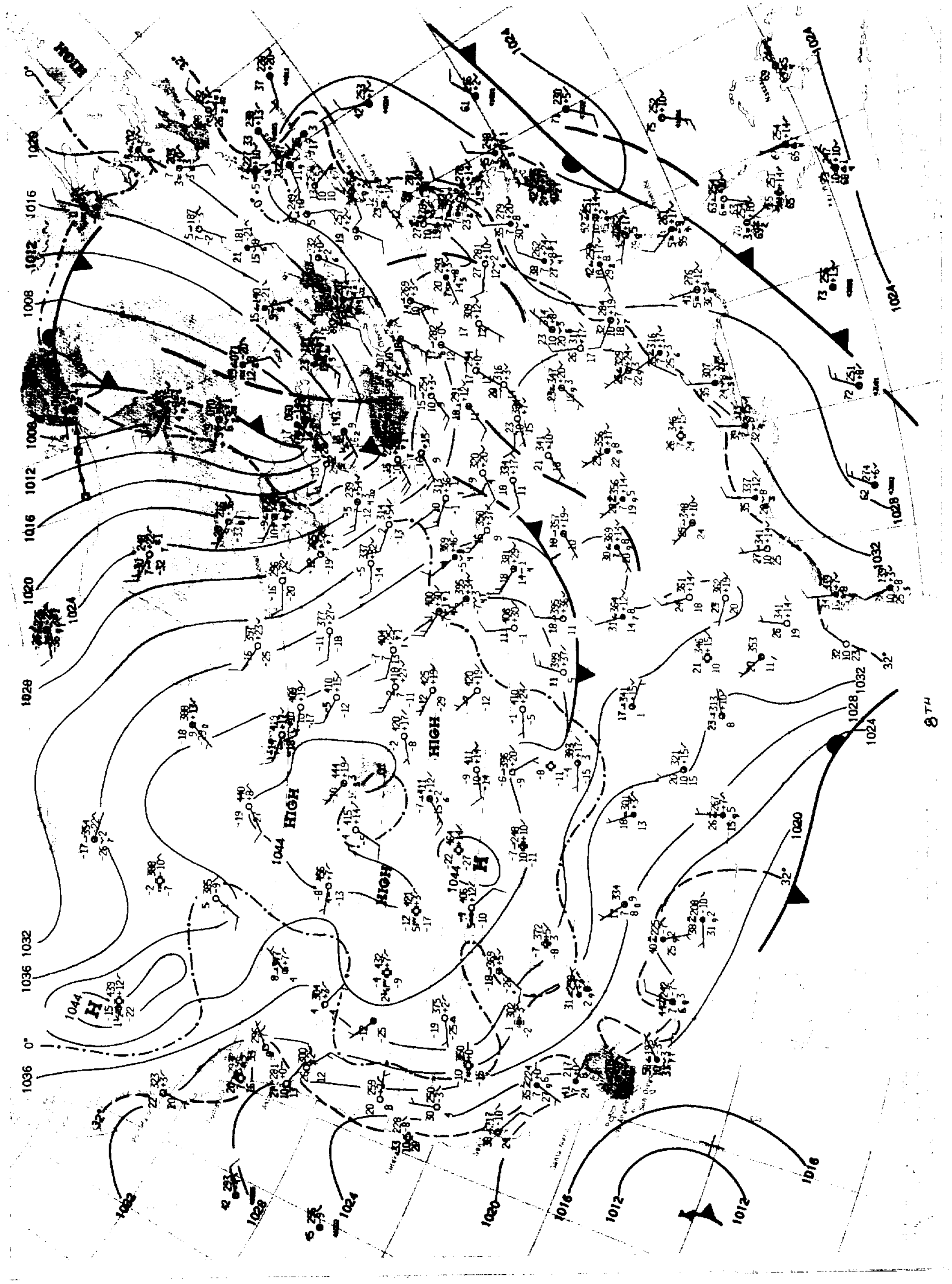


Figure A-8. Surface Analysis on 8 February 1989 at 1200 UTC.

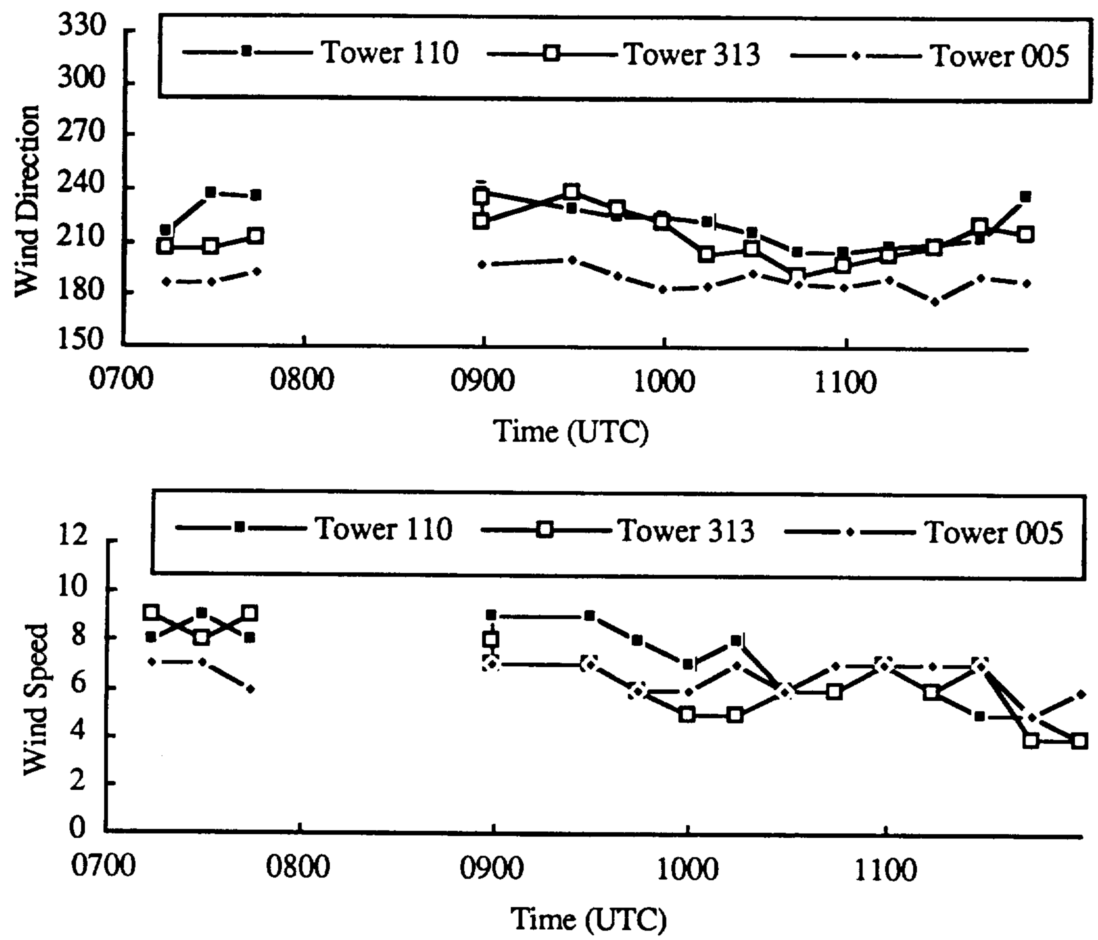
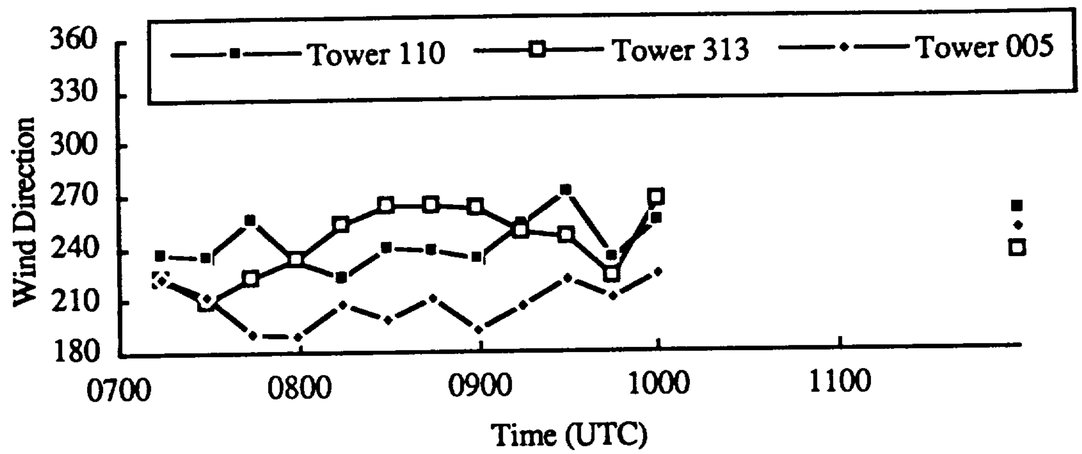


Figure A-9. CCAFS 54 ft Wind Tower Data for 0700-1200 UTC on 7 February 89, See Figure 1.2 for Tower Locations.

For the remainder of 7 February, the low-level flow remained south to southwest with a sea breeze reported at most coastal stations late in the afternoon. TTS reported a south-southeast flow from 2100 UTC to 0300 UTC. There was a stronger sea breeze from PAFB and Melbourne southward to Vero Beach as their winds shifted to east-southeast at 10 knots. The onshore sea breeze flow raised dew points 1-2°F and lowered temperatures into the upper 70s (°F).

As the cold front approached central Florida on 8 February, the low-level flow switched from southwest to west and eventually to northwest As shown by Cape Canaveral wind towers (see Figure A-10.) the flow at 0700 UTC was southwest to west but became more west between 0800 to 1000 UTC. Wind speeds throughout the early morning hours were generally 5 knots or less. These light winds are also evident in the 1200 UTC CCAFS sounding (Figure A-11) on 8 February. This sounding also shows an isothermal layer from the surface to just above 1000 mb with significant moisture up to 850 mb and drying above 700 mb.



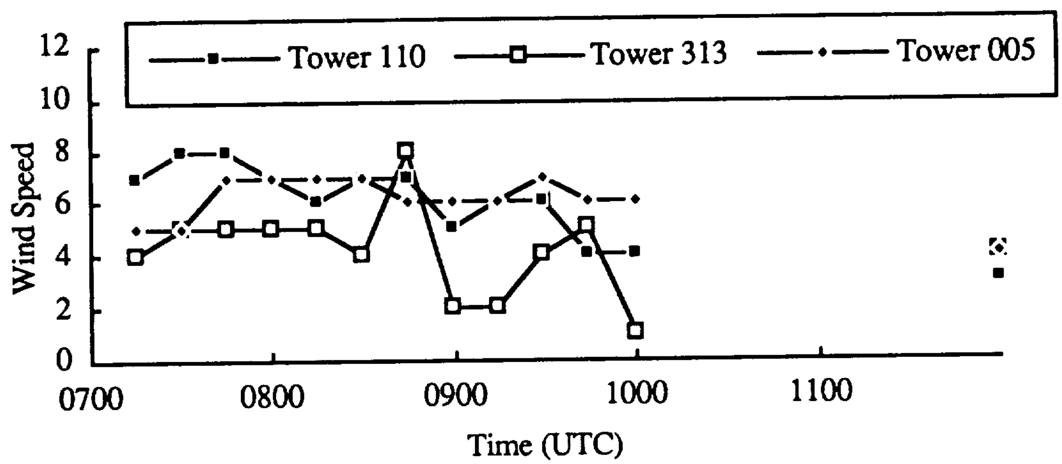


Figure A-10. CCAFS 54 ft Wind Tower Data for 0700-1200 UTC on 8 February 89, See Figure 2 for Tower Locations.

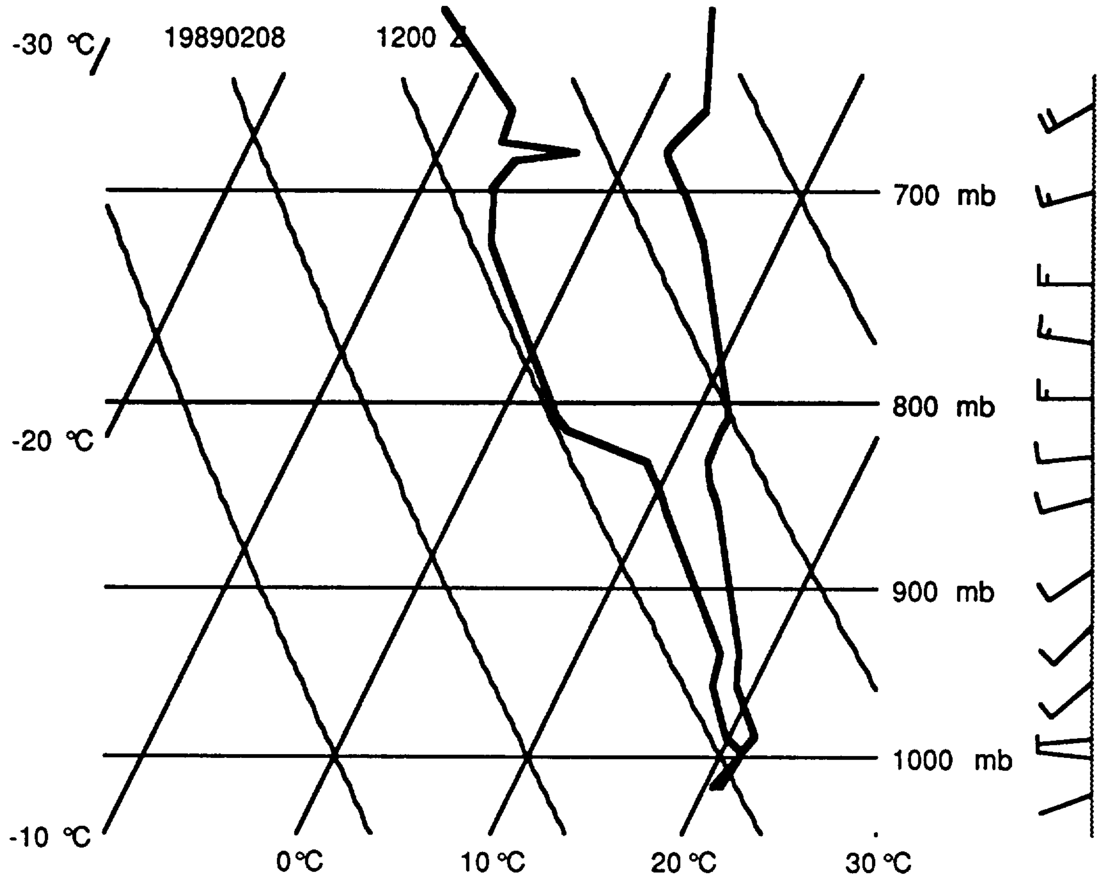


Figure A-11. CCAFS Sounding at 1200 UTC on 8 February 1989

On 8 February, the first fog report in central Florida was at Daytona Beach at 0650 UTC (6 miles visibility) with thicker fog (3/8 mile visibility) developing between 0800 and 0900 UTC. Fog was not reported in the Orlando region until 1100 UTC. Fog was reported at TTS at 1203 UTC approximately 2 hours after the northwest wind shift occurred over Cape Canaveral (see wind tower plots). By 1300 UTC the flow continued to be from the northwest at 5-8 knots at TTS with thicker fog being advected from the northwest and visibility decreasing to less than 1 mile. Fog continued to restrict visibility until 1530 UTC at TTS with lower stratus persisting until 1700 UTC. By 1800 UTC the fog and stratus had lifted allowing temperatures to rise to near 80 °F with only cumulus and higher level cirrus reported. Winds over the area continued to be from the west at around 5 knots. The cold front passed the Cape region at 2000 UTC with the flow becoming northerly at 10-15 knots. Behind the front lower stratus clouds moved into the area from the north with temperatures dropping down into the lower 70s (°F) by 2100 UTC.

Key Points (Precursors) from Analysis of 7-9 February 1989

- Approaching cold front over Florida caused the lower level winds to change considerably during 7-8 February 1989. Low-level winds at TTS shifted from south-southwest on 7 February to west and northwest on 8 February.
- As the cold front approached TTS, the lower level winds weakened from 10 knots on 7 February to 5 knots or less on 8 February. This reduced vertical mixing and facilitated fog formation in the boundary layer.
- Fog first formed to the northwest on 8 February (i.e., Daytona Beach) at least 2-3 hours before onset at TTS.
- Fog occurred at TTS approximately 2 hours after a wind shift from west to northwest over the Cape wind tower network.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1994	Contractor Report

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Analysis of Rapidly Developing Fog at the Kennedy Space Center, 1986 -1990, Final Report	C-NAS10-11844
6. AUTHOR(S)	
Mark M. Wheeler, Michael K. Atchison, Robin Schumann, Greg E. Taylor, Ann Yersavich, John D. Warburton	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
ENSCO, Inc., 445 Pineda Court, Melbourne, FL 32940	94-002
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA, John F. Kennedy Space Center, Code TM-LLP-2, Kennedy Space Center, FL 32899	CR-195888

11. SUPPLEMENTARY NOTES

Subject Cat.: #47 (Weather Forecasting)

12A. DISTRIBUTION/AVAILABILITY STATEMENT	12B. DISTRIBUTION CODE
Unclassified - Unlimited	

13. ABSTRACT (Maximum 200 Words)

This report documents fog precursors and fog climatology at Kennedy Space Center (KSC) Florida from 1986 to 1990. The major emphasis of this report focused on rapidly developing fog events that would affect the less than 7-statute mile visibility rule for End-Of-Mission (EOM) Shuttle landing at KSC (Rule 4-64(A)). The AMU's work is to: develop a data base for study of fog associated weather conditions relating to violations of this landing constraint; develop forecast techniques or rules-of-thumb to determine whether or not current conditions are likely to result in an acceptable condition at landing; validate the forecast techniques; and transition techniques to operational use. As part of the analysis the fog events were categorized as either advection, pre-frontal or radiation. As a result of these analyses, the AMU developed a fog climatological data base, identified fog precursors and developed forecaster tools and decision trees. The fog climatological analysis indicates that during the fog season (October to April) there is a higher risk for a visibility violation at KSC during the early morning hours (0700 to 1200 UTC), while 95% of all fog events have dissipated by 1600 UTC. A high number of fog events are characterized by a westerly component to the surface wind at KSC (92%) and 83% of the fog events had fog develop west of KSC first (up to 2 hours). The AMU developed fog decision trees and forecaster tools that would help the forecaster identify fog precursors up to 12 hours in advance. Using the decision trees as process tools ensures the important meteorological data are not overlooked in the forecast process.

With these tools and a better understanding of fog formation in the local KSC area, the Shuttle weather support forecaster should be able to give the Launch and Flight Directors a better KSC fog forecast with more confidence.

14. SUBJECT TERMS	15. NUMBER OF PAGES 67
Space Shuttle, Fog, Climatology, Weather Analysis, KSC	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	NONE